Reg Environ Change (2017) 17:777–787
DOI 10.1007/s10113-016-1070-8

ORIGINAL ARTICLE

Land cover dynamics in the Simien Mountains (Ethiopia), half a century after establishment of the National Park

Miro Jacob[1] · Amaury Frankl[1,5] · Hans Hurni[2] · Sil Lanckriet[1] · Maaike De Ridder[3] · Etefa Guyassa[1,4] · Hans Beeckman[3] · Jan Nyssen[1]

Received: 19 April 2015 / Accepted: 10 October 2016 / Published online: 2 November 2016

Abstract The Simien Mountains house several endangered and endemic wildlife species and provide important ecosystem services. Despite its regional environmental importance, the Simien Mountains are listed as World Heritage in Danger since 1997. This raised the need for an evaluation of landscape changes from before the establishment of the Simien Mountain National Park (SMNP) in 1969. For this purpose, historical terrestrial photographs (1966–2009) were re-analyzed from 2014 repeats, using an expert rating system with eight correspondents. An increase in forest was observed in the eastern and western edge of the SMNP at Sankaber and Imet Gogo (20–40%). In contrast, centrally in the SMNP (around Gich), the area covered with dense forest decreased with an estimated rate of −1.4% per decade. There is no significant effect ($p > 0.05$) of the boundary of the SMNP on woody vegetation change, because of continued anthropogenic pressure (especially wood cutting and livestock grazing) inside the SMNP. Also elevation and distance to scout camps do not affect rates of change, and however, the density of houses within 2.2 km (a proxy of population pressure) is able to explain 32% of the spatial distribution of woody vegetation decrease ($p < 0.05$). A subset of six repeated photographs, indicated an uplift of the treeline by more than 1 m year^{-1}, in areas with low anthropogenic pressure. This is potentially related to increasing (average annual) temperature warming of up to 1.5 °C over the past 50 years. Overall, further reduction in anthropogenic pressure is urgent and crucial for recovery of the afro-alpine vegetation and the interrelated endangered wildlife in the Simien Mountains.

Keywords Vegetation change · Treeline dynamics · Anthropogenic pressure · Repeat photography

Editor: Sarah Gergel.

Electronic supplementary material The online version of this article (doi:10.1007/s10113-016-1070-8) contains supplementary material, which is available to authorized users.

✉ Miro Jacob
Miro.Jacob@UGent.be

Amaury Frankl
Amaury.frankl@UGent.be

Hans Hurni
Hans.Hurni@cde.unibe.ch

Sil Lanckriet
Sil.Lanckriet@UGent.be

Maaike De Ridder
Maaike.de.ridder@africamuseum.be

Etefa Guyassa
EtefaGuyassa.Dinssa@UGent.be

Hans Beeckman
Hans.beeckman@africamuseum.be

Jan Nyssen
Jan.Nyssen@UGent.be

1 Department of Geography, Ghent University, Krijgslaan 281 S8, 9000 Ghent, Belgium

2 Centre for Development and Environment (CDE), University of Bern, Hallerstrasse 10, 3012 Bern, Switzerland

3 Laboratory for Wood Biology and Xylarium, Royal Museum for Central Africa, Leuvensesteenweg 13, 3080 Tervuren, Belgium

4 Department of Land Resource and Environmental Protection, Mekelle University, Mekelle, Ethiopia

5 Research Fund – Flanders (FWO), Egmontstraat 5, 1000 Brussels, Belgium

Introduction

Since the introduction of agriculture, land use has altered the process of land cover changes (Goudie 2006; Houghton 1994). At present, land use and land cover (LUC) dynamics form one of the key research imperatives in the global change framework (Geist and Lambin 2001). African tropical mountain areas generally have a greater vulnerability to LUC changes due to the high population density and the presence of steep slopes (Lambin 1997). LUC change studies in the north Ethiopian highlands indicated that the highland vegetation significantly changed during the second half of the twentieth century (Bewket 2002; de Mûelenaere et al. 2014; Tegene 2002; Tekle and Hedlund 2000; Zeleke and Hurni 2001). Most of these studies focus on LUC changes in the subalpine highlands and indicate a trend of deforestation in favor of cultivation land. However, little is known about vegetation changes in the upper afro-alpine zone and about changes in the treeline at this elevation. Wondie et al. (2011) studied land cover changes in the Simien highlands from Landsat images of 1984 and 2003 and indicated an increase in the *Erica* forest and a decrease in the agricultural land. Wondie et al. (2011) also stress the need for more land cover change studies, going back to the origin of the National Park in 1969. This is especially interesting, because the Simien highlands have a long-lasting history of intensified land use.

Improved understanding of the high-altitude afro-alpine vegetation is important given the ecosystem services provided by the afro-alpine vegetation (Aerts et al. 2002; Miehe and Miehe 1994). The afro-alpine forest with its woody and epiphytic biomass is important for providing forest products, for storing carbon dioxide, for slope stability and regionally as a hygric buffer (Miehe and Miehe 1994; Markart et al. 2007). The mountain forests play a key role in the ecosystem stability by capturing and storing rainfall, regulating flows, reducing soil erosion and protecting against floods, landslides and rock fall (Aerts et al. 2002; Miehe and Miehe 1994). The ecology and richness of the highland vegetation play a vital role for clean and steady water discharge. These mountain environments are also 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 et al. 2006). The afro-alpine vegetation of the Ethiopian highlands provides a habitat for several endangered endemic species such as the iconic and severely endangered Ethiopian wolf (*Canis simensis*) and Walia ibex (*Capra walie*) (Marino 2003). Because of the potential impact of climate change on the important ecosystem services of the afro-alpine vegetation, a better understanding of vegetation dynamics in the African tropical highlands is needed.

Repeat photography proved to be a valuable tool to study such long-term landscape changes (Webb et al. 2010). Historical photographs contain detailed landscape information, which is not documented by systematic aerial photography and satellite imagery (Roush et al. 2007). Repeat photography has been used in a wide range of applications (Webb et al. 2010): documenting gully head retreat rates (e.g., Frankl et al. 2012), long-term environmental changes (e.g., Nyssen et al. 2014a), vegetation changes (e.g., Pickard 2002), glacier fluctuations (e.g., Roush et al. 2007) and plant phenology (e.g., Crimmins and Crimmins 2008).

In addition, vegetation cover changes in the Simien Mountains are also important in the context of climate change. Average temperatures have risen worldwide during the past century, a change that is most prominent and rapid at high altitudes and latitudes (Harsch et al. 2009). The temperature-sensitive upper *Erica arborea* L. forest in the Simien Mountains is potentially responsive to climate warming (Holtmeier and Broll 2005). Consequently, this vegetation belt can be studied to highlight effects of global warming (Holtmeier and Broll 2007). The high-altitude forest limit is one of the most apparent vegetation boundaries worldwide. The transition from closed montane forests to treeless afro-alpine vegetation forms a steep gradient where the treeline ecotone may contain fragmented forest stands with stunted trees (Körner and Paulsen 2004). The response of the treeline ecotone to the present climate change in the tropics and in the southern hemisphere is scarcely investigated compared to treeline dynamics at higher northern latitudes (Holtmeier and Broll 2007). Jacob et al. (2015) reviewed treeline dynamics in the African tropical highlands and demonstrated that treelines are, in general, limited below their climatic limit due to high anthropogenic influences, but many uncertainties remain. The aim of this study is to detect both land cover changes and treeline dynamics in the afro-alpine belt of the Simien Mountains using repeat photographs (1966–2014) and to understand the biophysical and social drivers of these changes.

Materials and methods

Study area

The Simien massif (13°14′ N, 38° 21′ E) is home to the highest peak of Ethiopia, the Ras Dejen Mt (4540 m) (Fig. 1). The massif is a remnant of a major Oligo-Miocene shield volcano, deeply eroded by the Tekeze River and its tributaries, which practically encircles the massif (Kieffer et al. 2004). The high Simien Mountains form the most northern limit of glaciation in East Africa during the LGM

(Hendrickx et al. 2015; Hurni 2015). The mountain climate of the Simien Mountains is characterized by frequent frost, occasional snow at high elevations and frequent hailstorms (Hurni 1988; Sebald 1968). Mean daily temperature ranges between minimum 1.5 °C and maximum 14.6 °C (Hurni and Stähli 1982). Rainfall in the Simien Mountains follows a unimodal rainfall pattern with high mean annual rainfall, 1515 mm at Gich camp (Hurni and Stähli 1982). The rainfall decreases from north to south in the Simien Mountains, associated with the 1000-m-high escarpment. At the end of the rainy season, in the period of September–October, clear mornings are frequently followed by a strong buildup of fog and cause heavy rain and hailstorms at night (Hurni and Stähli 1982).

The SMNP was created in 1969, a period when 80% of the park was subjected to human use through livestock grazing, cultivation and settlements (Debonnet et al. 2006). Population growth forced people to cultivate higher and on steeper areas, even marginal lands up to 3800 m a.s.l. were converted into cultivation land (Keiner 2000). The stocking density in the SMNP is also high (up to 55 Tropical Livestock Units (TLU)/km^2 in Gich) which affects the afro-alpine grasslands at higher elevations through home herding (Keiner 2000). In 1978, the park was listed as World Heritage and in 1997 due to the continued population pressure and decline of the flagship species as World Heritage in Danger. At present, the number of tourists in the SMNP has grown which has strengthen conservation, but at the same time there is a significant risk that poorly regulated tourism development will become problematic for the SMNP environment (EWCA 2015).

The vegetation in the Simien Mountains can be classified according to three distinct elevation belts. Between 2000 m and up to 3500 m NE and 3300 m SE the evergreen afro-montane forest prevails. This belt is rich in species with large trees such as *Prunus africana* and *Hagenia abyssinica* at the wetter northern slopes and dominated by *Olea europaea* subsp. *cuspidate* at the drier south-southeast-facing slopes. *Juniperus procera* is less common in the Simien Mountains (Friis and Ryding 2001). The ericaceous belt between 2900 and 3700 m includes the tree heather *Erica arborea* joined by *Hypericum revolutum*, as well as *Nuxia congesta* in the lower elevations (Klötzli 1958; Nievergelt et al. 1998). Above 3700 m, the afro-

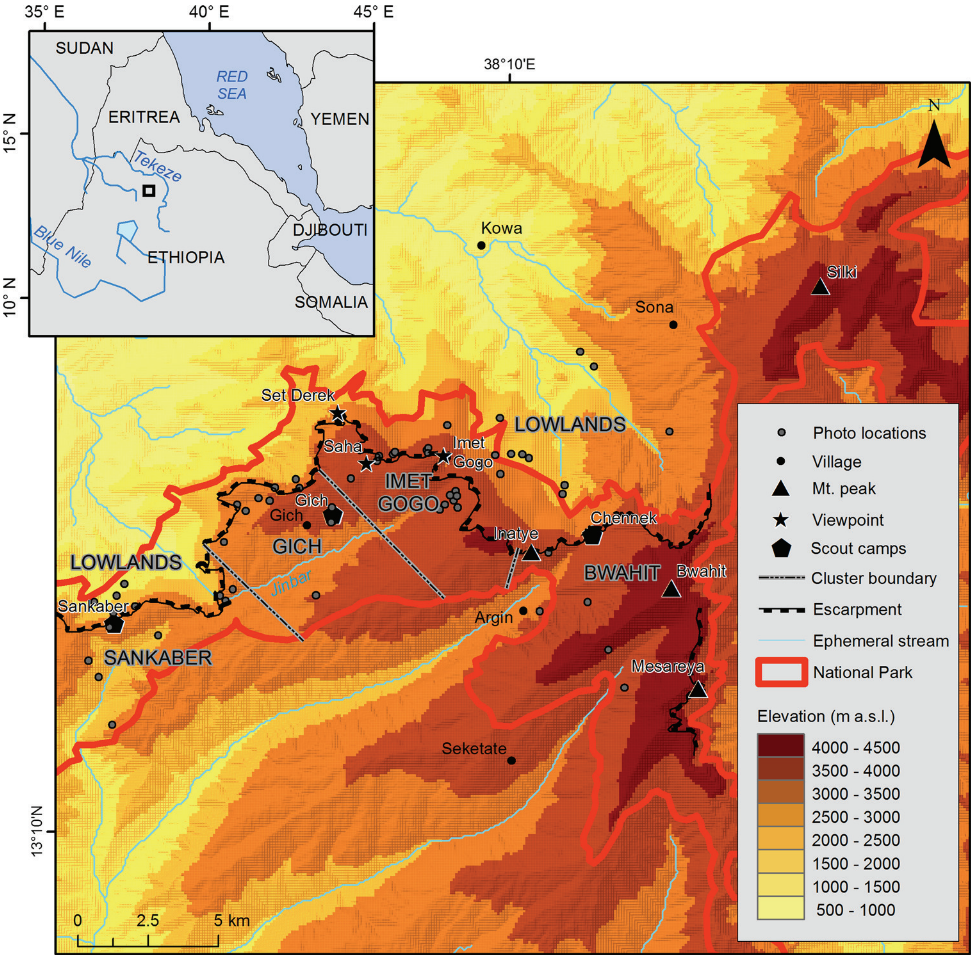

Fig. 1 Location of the study area with indication of the approximate cluster boundaries; the boundary of the Kona-Sona lowlands is formed by the northern escarpment. In the south the boundary is less sharp

alpine zone prevails with afro-alpine grasslands dotted with giant Lobelias (*Lobelia rhynchopetalum*) and different types of short- and long-grass steppes (*Festuca macrophylla, Carex erythrorhiza*) and mires (Hurni and Stähli 1982). The Simien Mountains are home to several endemic species, of which many are endangered due to habitat fragmentation and destruction caused by human impact (Alemayehu et al. 2011; Yihune et al. 2009). In 2009, the UNESCO and IUCN initiated a joint mission to assess the state of the SMNP and to guide the park toward a state that would justify its removal from the World Heritages in Danger (Debonnet et al. 2006).

Repeat photography

For this study, 98 terrestrial oblique photographs of the Simien Mountains were collected dating back between the 1960s and 2009 (Table 1). The photographs were originally taken by Bernhard Nievergelt, Larry Workman, Hans Hurni and Jan Nyssen during various expeditions in the Simien Mountains. The photographs were selected because they give a unique representation of historical vegetation cover on the slopes of the Simien Mountains. With the aim of comparing the past vegetation cover with the current situation, the photographs were repeated in November 2014. The viewpoint of the photographs was relocated using the photo metadata and through pre-screening of the landscape in Google Earth. The exact camera position requires precise repositioning of the camera and the photocomposition (Hall 2001). To achieve this, near and distant objects were mentally lined up in the field in a triangulation system (Nyssen et al. 2009b). Several photographs were taken along two lines crossing (with a 90° angle) at the relocated camera position and the best fit was selected on-screen (Frankl et al. 2011). To reduce geometrical errors, the skyline and topography from the historical photographs were used as reference to slightly rotate, rescale and crop the repeated photographs (Frankl et al. 2011).

Expert ratings and vegetation change

Land cover changes between the photo-couples were analyzed by eight scientists with a longstanding research experience in vegetation dynamics in the Ethiopian highlands or elsewhere. They originate from four different research institutes: the physical research group of Ghent University, the laboratory of Wood Biology and Xylarium from the Royal Museum for Central Africa, The Centre for Development and Environment of Bern University and the department of Land Resource and Environmental Protection from Mekelle University. To avoid bias, uninterpretable areas due to foreground errors, shadows or obstructions were masked on each photograph of each photo-pair used for comparison. In addition, photographs representing different major topographic entities were split in separate photographs for evaluation. The 98 historical photographs represent 59 different photo-locations, because some landscapes have been repeatedly photographed at different time steps.

The expert evaluation was performed on these 59 photo-locations subdivided in 98 on-screen photo-pair interpretations (multiple photographs per site). The experts estimated the land cover distribution as a percentage of the complete scenery (online resource 1) (Nyssen et al. 2014b). Based on field experience, nine major land cover classes were determined:

- Areas covered by forest. Subdivided between (1) open forest if the wooded area has <50% canopy cover and (2) dense forest if the canopy cover is >50%.

Table 1 Historical photographs used in analysis ($n = 98$)

Year	Authors	Photographs	Photo-cluster location
1966–1968	Bernhard Nievergelt[a]	6	Bwahit, Gich, Imet Gogo
1971–1978	Bernhard Nievergelt[a]	5	Gich, Imet Gogo, Lowlands
	Larry Workman[b]	13	Imet Gogo, Lowlands, Sankaber
	Hans Hurni[c]	10	Bwahit, Imet Gogo, Lowlands
1980–1983	Bernhard Nievergelt[a]	5	Gich, Imet Gogo, Lowlands
	Hans Hurni[c]	19	Gich, Lowlands, Sankaber
1993–1999	Bernhard Nievergelt[a]	9	Bwahit, Gich, Imet Gogo, Lowlands
	Hans Hurni[c]	25	Bwahit, Gich, Imet Gogo, Lowlands
2009	Jan Nyssen[d]	6	Bwahit, Gich, Lowlands

[a] Nievergelt et al. (1998)

[b] Private collection

[c] Centre for Development and Environment, University of Bern

[d] Department of Geography, Ghent University

- Shrubland: areas dominated by shrubs, generally emitted to surface cover only (e.g., *Solanum sessilistellatum, Rosa abyssinica*).
- Grasslands: areas covered by grass species such as *Danthonia, Festuca* or *Koeleria*. A subdivision between short-grass steppe (if 20–40 cm high) and long-grass steppe (if 40–80 cm) (Nievergelt et al. 1998) proved difficult for the interpretation.
- Lobelia: areas covered by *Lobelia rhynchopetalum*.
- Cultivation lands: areas under crops and fallow land.
- Rock outcrop: non-vegetated areas dominated by outcropping rock.
- Settlements and infrastructure: areas dominated by the presence of buildup areas (i.e., roads, campsites, houses).

The recommendations of Nyssen et al. (2014b) were adopted to correct the landscape evaluation for outliers. This implies that for every photo-couple, the two interpretations with the largest deviation were excluded from the calculation of the average photo-interpretation. From the remaining interpretations, the average land cover change was calculated for each class. In order to compare these rates between the photo-couples, the annual rate of change was derived by dividing the difference in area occupied by each land cover class by the number of years between the photographs. From this annual rate of change, the decadal change was derived through multiplication with 10 in line with Masubelele et al. (2015). For further analysis, the individual observations were clustered by altitudinal belts and sites, i.e., the Sankaber, Bwahit, Gich, Imet Gogo mountain areas and the lowland (2000–3000 m a.s.l.) areas. These five clusters are used to describe and compare land cover dynamics in the Simien Mountains.

Woody vegetation

The land cover classes shrubland, open and dense forest were summed to derive a value for changes of the woody vegetation in the Simien Mountains. To understand temporal changes in woody vegetation since inscription on the World Heritage list in 1978, the observations were divided in two periods 1966–1978 and 1980–2009 in comparison with the current situation (2014). The land cover changes were subdivided in two temporal periods because (1) the SMNP was enlisted on the World Heritage list in 1978 and (2) the temporal range of the photographs can be grossly divided in two groups. The changes are mapped for the area within a range of 2.2 km around the observation (center of the pictured landscape) using inverse distance weighting (IDW) interpolation with smooth function (ArcGIS). This distance corresponds with the daily travel range of herders (Nyssen et al. 2009a). The 1000-m-high escarpments form a structural boundary in the landscape and are therefore set as a hard boundary limiting the interpolated influence zone of the observations.

In order to explain the observed spatial pattern of woody vegetation changes in the Simien Mountains, four potential explanatory factors were measured for every observation: (1) inside or outside the National Park boundary, (2) elevation, (3) population density and (4) distance to the nearest scout camp. The population density is derived from the density of houses within 2.2 km of the observation point, taking into account the escarpment as a topographic boundary. A one-way ANOVA test was used to test whether there is a significant difference between the areas outside and inside the National Park and a multiple linear regression was used to estimate the effect of population density, distance to scout camp and elevation on woody vegetation change.

Treeline repeats

The *Erica* treeline is visible for four different mountain slopes on nine photo-pairs. These photographs are valuable since they provide long-term detailed evidence on treeline dynamics. The procedure of Van Bogaert et al. (2011) was used to study such dynamics. In this procedure, the physiognomic treeline boundary is set to 30% tree cover and prominent landmarks at the vicinity of the historical treeline are used as a proxy for the historical treeline elevation. Therefore, the 30% forest cover boundary is delimited with an isoline on the photograph, and global navigation satellite system (GNSS) points were collected from landmarks and from the current treeline elevation. Consequently, treeline dynamics were derived from the difference in elevation between the landmark and the current treeline. In order to compare treeline shift between the photo-pairs (with different time spans), the annual shift rate was calculated assuming a linear advance in time. A similar approach was used to study differences in the upper tree limit for 6 photo-locations (11 photo-pairs), using elevations of the upper individuals derived from Google Earth.

Results

Vegetation cover change

In the highlands, grassland is the most important land cover class, and it ranges between 33 and 67% of the total vegetation cover. This is, however, decreasing around Sankaber (−4%) and Imet Gogo (−9%), where grassland is removed in favor of woody vegetation. Beside grassland, rock outcrop is also decreasing in most sites. On the other hand, cropland increased in the Kona-Sona lowlands (+1%) and also in the highlands in Gich (+2%) and around Bwahit (+2%) area (online resource 2).

Decadal changes (Fig. 2) indicate an increase in the dense forest in all areas except in Gich. There, the dense forest decreased with a rate of −1.4% of the total area per decade and also the area covered by grasslands is decreasing, while cropland is the most important growing class (+1% per decade). Around Bwahit, there is also a considerable increase in the area covered by cropland (+0.5% per decade). Although dense forest increased around Bwahit, open forest and bushland decreased here. The cropland area also increased in the Kona-Sona lowlands (+0.2% per decade). However, the most important increasing class in the Kona-Sona lowlands is dense forest with +1.4% per decade at the expense of open forest, grassland and rock outcrop. Vegetation cover similarly increased around Sankaber and Imet Gogo; in both areas grassland decreased in favor of dense and open forest. The increase in dense forest is especially high in Imet Gogo (+1.4% per decade).

Woody vegetation change

The average woody vegetation change is negative (−1.8%) outside the SMNP and positive (1.4%) inside the SMNP, but an ANOVA test shows that this difference is not significant for all time periods ($p > 0.05$) (online resource 3). The boundary of the National Park is not significantly explaining for changes to woody vegetation in the Simien Mountains. This absence of impact of the National Park is also visible on the woody vegetation cover change map for the period after 1978 (Fig. 3). Changes in the woody vegetation after 1978 are limited throughout the study area, the majority of observations showing a small increase. The observed changes since the period before 1978 are more diverse. Around Gich, woody vegetation clearly decreased (−30 to −10%), while around Sankaber and Imet Gogo there is a remarkable increase in woody vegetation (20–40%). In online resource 4, such increase in woody vegetation at the Jinbar valley (part of the Imet Gogo cluster) is illustrated by a sequence of repeated photographs. Over the full period, woody vegetation slightly increased in the major part of the study area, except for decreasing woody vegetation areas around Gich, Argin and in the Kona-Sona lowlands and strongly increasing woody vegetation around Sankaber and Imet Gogo (Fig. 3).

Elevation and distance to scout camps are not significant as explanatory variables for the observed pattern of woody vegetation change ($p > 0.05$), but the density of houses is significant ($p < 0.05$). The density of houses in a zonation

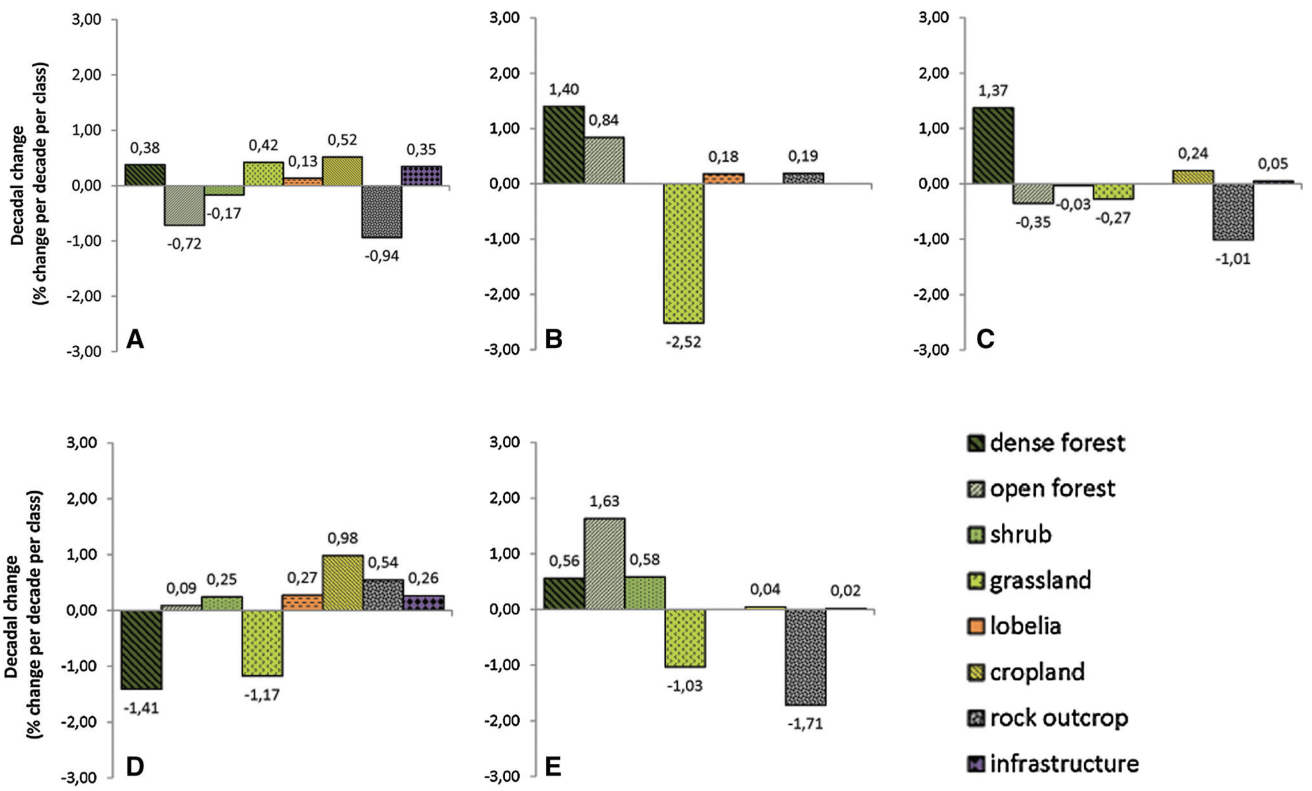

Fig. 2 Decadal land cover changes in the Simien Mountains as derived from repeat photographs for **a** Bwahit area, **b** Imet Gogo area, **c** Lowland areas north of the escarpment, **d** Gich area and **e** Sankaber area

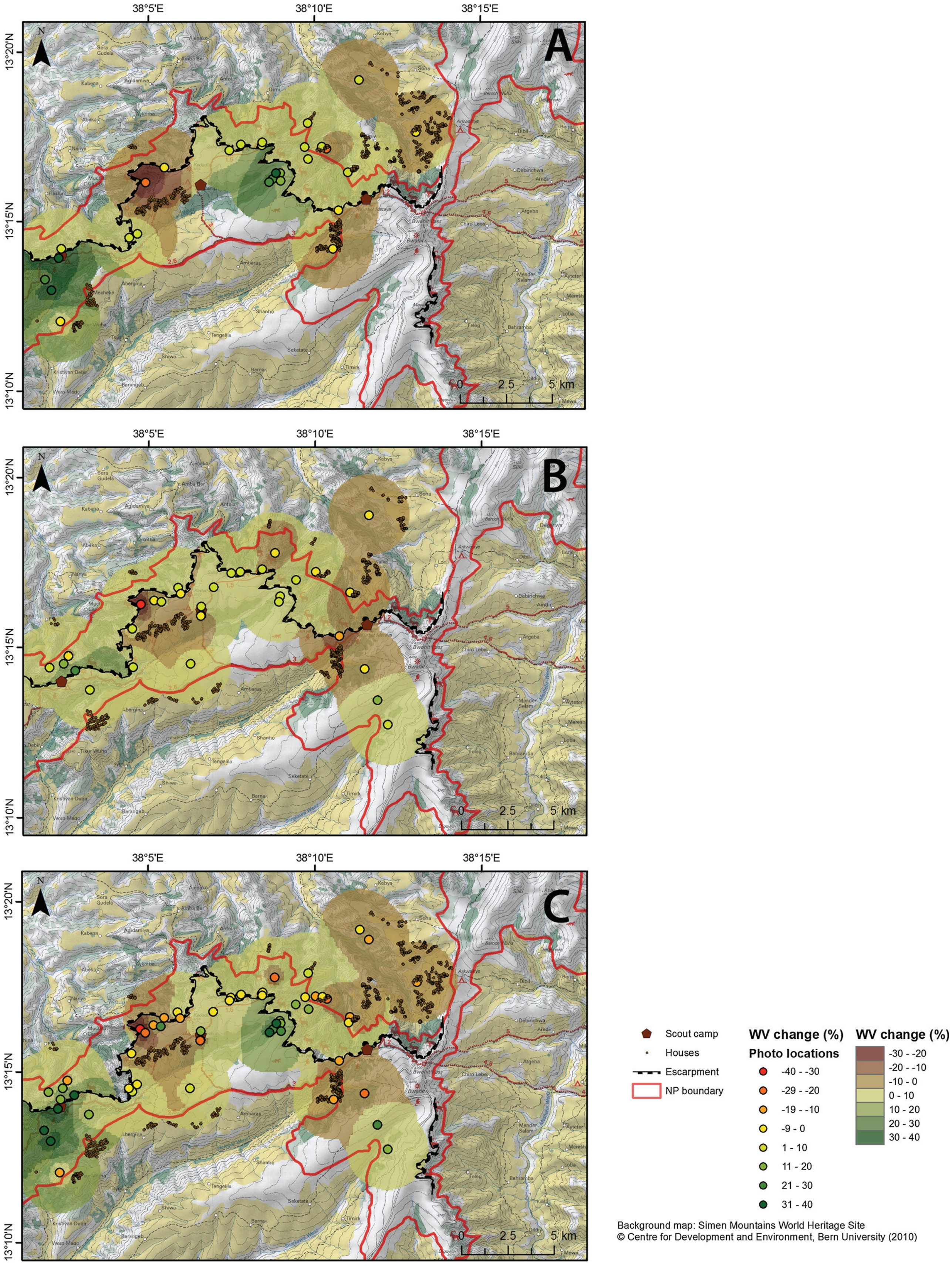

Fig. 3 Woody vegetation (WV) cover change maps for 2014, as compared to **a** 1966–1978, **b** 1980–2009 and **c** 1966–2009

of 2.2 km, around the center of the pictured landscape, is used as a proxy for the population pressure and explains 32% of the observed spatial variation for the total period (online resource 3).

Treeline dynamics

The elevation of the present physiognomic treeline is situated between 3810 m in Jinbar valley and 4005 m upslope from Argin village. Similarly, the upper individuals are situated at 3827 m in Jinbar valley and 4053 m, upslope from Argin village. On the Set Derek and Saha photographs, there are no *Erica arborea* trees in 1973. But, on the recent photographs in 2014, shrub-sized *Erica* trees appear. The upper tree limit is thus shifting upwards.

Repeated photographs of the treeline indicate a treeline rise in all pictured sites, but there are many local differences (Table 2). The average annual rise of the physiognomic treeline is 1.1 m but with a large standard deviation (0.9 m). The upward shift of the upper treeline is faster with 2.6 ± 1.6 m per year on average. The annual rise of the treeline is especially high at Inatye mountain with 5.1 m year^{-1} between 1966 and 2014. The physiognomic treeline in Jinbar valley shifted upwards with 1.5 m year^{-1} since 1966. As stated before there was a fire in the 1970s; after this fire the upward shift continued at a similar rate (1.1 m year^{-1} since 1978). In Seketate (online resource 5) and Argin valley, the physiognomic treeline rose, respectively, with 2.5 and 3.1 m year^{-1} during the last 20 years (since 1994).

Discussion

Land use and National Park management

Remarkably, the establishment of the National Park did not induce a significant increase in woody vegetation. This can be partly explained by early colonization of marginal lands in the Kona-Sona lowlands outside the NP, which leaves limited space for further expansion of the cultivation land. In fact, a reversal has been observed whereby abandoned marginal cultivated lands on steep slopes in the Kona-Sona lowlands have been revegetated (online resource 6). On the other hand, continued anthropogenic pressure within the National Park is responsible for the lack of differences seen across the National Park boundary. The area covered by grassland is relatively stable; it is only lost to forests in Sankaber and in Imet Gogo. Unfortunately, this study gives no insight into the condition of the grassland. Nevertheless, the condition of the grass is of key concern for the ecosystem. The SMNP survey of 1996 indicated that only 15% of the grass in the SMNP was in a natural state, while 25% was heavily overgrazed and 60% heavily grazed (Nievergelt et al. 1998). Livestock pressure is even increasing due to a ban on the expansion of cultivation land in Gich. The people shifted their livelihood strategy toward increased livestock in reaction to this limitation of the cultivation land (Debonnet et al. 2006).

During the civil war in 1985, rebels occupied the SMNP. Although the Walia ibex population was heavily poached in that period, the natural resources of the park were not

Table 2 Dynamics of the upper and physiognomic treeline derived from repeat photographs of the Simien Mountains

	Slope exposition	Peak (m asl)	Interval	Years	Upper individuals		Shift (m)	Physiognomic treeline		Shift	Annual rate (m year^{-1})	
					Old	New		Old	New		*p–t*	*u–t*
Jinbar valley	SE	4051	1966–2014	48	3791	3827	36	3736	3810	74	0.8	1.5
			1973–2014	41	3812	3827	15	n/a	0.4	n/a		
			1978–2014	36	3821	3827	6	3771	3810	39	0.2	1.1
			1993/1994–2014	21	3827	3827	0	3787	3810	23	0	1.1
Inatye Mt.	NW	4070	1966–2014	48	3791	3900	109	3631	3876	245	2.3	5.1
			1996–2014	18	3876	3900	24	3791	3876	85	1.3	4.7
Seketate valley	NW	4181	1994–2014	20	3991	4040	49	3941	3991	50	2.5	2.5
	SE	4237	1994–2014	20	4020	4036	15	3940	3975	35	0.8	1.8
Argin village	E	4246	1994–2014	20	4005	4053	48	3941	4005	61	2.4	3.1
Set Derek	W	3913	1973–2014	41	<3830	3887	>57		n/a		>1.4	n/a
Saha		3785	1973–2014	41	<3700	3762	>62		n/a		>1.5	n/a

significantly affected (Debonnet et al. 2006). The area around Sankaber is the best protected area of the National Park, completely protected since 15 years (Hans Hurni, personal observations). Direct proximity to the guarded scout camp of Sankaber potentially explains the observed increase in woody vegetation. But the scout camps of Gich and Chennek have no positive effect on woody vegetation changes. Moreover, the areas surrounding Gich and Chennek camp show a decrease in the woody vegetation likely the result of the growing population in Gich and Argin. Strong human pressure on the environment was also observed in proximate mountain environments and National Parks (Mugagga et al. 2012). Severe erosion due to the replacement of forests by agriculture and settlements is observed in Mount Kilimanjaro (Soini 2005; Yanda and Shishira 2001), while at Mount Elgon similar anthropogenic disturbances cause an increase in landslides (Mugagga et al. 2012).

In contrast to our findings, Wondie et al. (2011) observed a decrease in cropland and an increase in forest between 1983 and 2003 in the SMNP. This decrease in cropland is mainly due to the abandonment of agricultural land below Sankaber camp between 1985 and 2003 (Wondie et al. 2011). However, there is no evidence for the existence of cropland in this area on the historical photograph of Larry Workman from 1973 (online resource 1). Nevertheless, both studies indicate an (on average) overall increase in dense forest (Wondie et al. 2011). Yet, more important are the spatial patterns of woody vegetation change, which are revealed in our study and indicate the negative influences of continued anthropogenic pressure.

The continued loss of woody vegetation at the village of Gich is clearly indicated in our study. This is a well-known concern for sustainable management of the SMNP. Previously in 1979, seven villages inside the National Park were moved out of the Park (Debonnet et al. 2006). The resettlement of Gich is part of a longstanding discussion and one of the priorities foreseen in the current plan of action. The villagers are encouraged to resettle on a voluntary basis to the town of Debark in exchange of land and compensation (EWCA 2015). Gich accounts for almost half of the remaining households in the National Park. Continued cultivation of the highly degraded croplands forms a serious threat. In Gich, the people are dependent on food aid for 5–6 months per year (EWCA 2015). Beside the resettlement of villagers, the park boundaries were realigned to exclude villages at the boundary of the park and at the same time to include Mesarerya and Lemalimo Wildlife Reserves. As a result, the park was expanded to almost 10,000 hectares and the population within the National Park was reduced to 1300 people (Debonnet et al. 2006) and a further expansion took place in 2008. These initiatives are part of the UNESCO/IUCN mission to guide the SMNP toward removal from the danger list.

Upwards shift of the Erica treeline

Upward movement of alpine trees, in areas under less anthropogenic pressure, was observed in the Simien Mountains (online resource 7). The observed shift near Seketate and Argin is remarkable given the vicinity of the villages of Seketate and Argin. However, at the ridge between the two valleys there is a scout house within 1 km from the upper forest of Argin and 2 km from the upper forest of Seketate. Evidence of an upwards shift of the upper treeline in the Simien Mountains, since the early twentieth century, is also given by Hurni (2005). Repeat photographs near the almost inaccessible Silki Mountain massif, between 1905 (from F. Rosen) and 2004, indicate a rise of the *Erica arborea* L. forests by about 150 m.

Such evidences of a risen treeline elevation in areas under low anthropogenic pressure suggest a potential climatic effect (Hurni 2005). The observed upward treeline shift of 150 m corresponds with a temperature effect between 0.5 and 1.5 °C since 1966, according to the altitudinal temperature lapse rate for East Africa of 0.6 °C per 100 m (Peyron et al. 2000). This indirect evidence of climate warming is of the same magnitude as the observed 0.37 °C increase per decade between 1951 and 2005 for Ethiopia (Tadege 2007). Similar vegetation responses to increasing temperatures in the Ethiopian Highlands, during the early Holocene (Umer et al. 2007) and after the Little Ice Age (Bonnefille and Umer 1994), are clearly demonstrated by ratios of Ericaceae pollen derived from the Bale and Arsi Mountains, respectively.

Conclusion

The Simien Mountains provide a habitat for several endangered endemic species and provide important ecosystem services to the environment. However, since 1997, the Simien Mountains have been listed as a World Heritage Site in Danger. Landscape changes derived from repeat photographs (from the period 1966–2009) indicate that the contemporary landscape (2014) is still under anthropogenic pressure. This is especially the case around the villages of Gich and Argin. On the other hand, this study also indicates that the woody vegetation has increased around Sankaber and Imet Gogo. Moreover, in locations isolated from anthropogenic pressure an increase in the upper treeline is observed, which is potentially related to a climate warming of 1.5 °C over the last 50 years. Continued reduction in the anthropogenic pressure, especially livestock grazing and wood cutting, is thus a key element for a recovery of the afro-alpine vegetation and associated wildlife habitat.

Acknowledgements This research was financially supported by the Belgian Special Research Fund (BOF fund, Ghent University) and was made possible by the Ethiopian Wildlife Conservation Authority, by Ato Girmay Ayalew in particular. Many thanks to Larry Workman and Bernhard Nievergelt for providing the historical photographs. We also thank the Wase-Tana Project (VLIR—Bahir Dar University) for their logistic support and the EWCA experts Ato Negussie Engdawork and Ato Azanaw Kefyalem as well as Yohannes Gebrehizir for field assistance. Thanks also goes to Silke Broidioi for her help and support.

Funding was provided by Ghent Special Research fund (Grant No. IV1).

References

Aerts R, November E, Behailu M, Deckers J, Hermy M, Muys B (2002) Forest rehabilitation: one approach to water conservation in central Tigray. Water Sci Technol 6:34–37

Alemayehu K, Dessie T, Gizaw S, Haile A, Mekasha Y (2011) Population dynamics of Walia ibex (*Capra walie*) at Simen Mountains National Park, Ethiopia. Afr J Ecol 49:292–300. doi:10.1111/j.1365-2028.2011.01264.x

Bewket W (2002) Land cover dynamics since the 1950s in Chemoga Watershed, Blue Nile Basin, Ethiopia. Mt Res Dev 22:263–269. doi:10.1659/0276-4741(2002)022[0263:LCDSTI]2.0.CO;2

Bonnefille R, Umer M (1994) Pollen-inferred climatic fluctuations in Ethiopia during the last 3000 years. Palaeogeogr Palaeoclimatol Palaeoecol 109:331–343. doi:10.1016/0031-0182(94)90183-X

Crimmins M, Crimmins T (2008) Monitoring plant phenology using digital repeat photography. Environ Manag 41:949–958. doi:10.1007/s00267-008-9086-6

de Mûelenaere S, Frankl A, Haile M, Poesen J, Deckers J, Munro N, Veraverbeke S, Nyssen J (2014) Historical landscape photographs for calibration of Landsat land use/cover in the Northern Ethiopian highlands. Land Degrad Dev 25:319–335. doi:10.1002/ldr.2142

Debonnet G, Melamari L, Bomhard B (2006) Reactive monitoring mission to Simen Mountains National Park. Joint World Heritage Centre-IUCN monitoring mission to Simen Mountains National Park World Heritage property. Paris, France

EWCA (2015) State of conservation report of the world natural Heritage site, Simen Mountains National Park (Ethiopia). Ethiopian Wildlife Conservation Authority, Addis Ababa, Ethiopia

Frankl A, Nyssen J, De Dapper M, Haile M, Billi P, Munro N, Deckers J, Poesen J (2011) Linking long-term gully and river channel dynamics to environmental change using repeat photography (Northern Ethiopia). Geomorphology 129:238–251. doi:10.1016/j.geomorph.2011.02.018

Frankl A, Poesen J, Deckers J, Haile M, Nyssen J (2012) Gully head retreat rates in the semi-arid highlands of Northern Ethiopia. Geomorphology 173–174:185–195. doi:10.1016/j.geomorph.2012.06.011

Friis I, Ryding O (2001) Biodiversity research in the Horn of Africa region. In: Proceedings of the third international symposium on the flora of Ethiopia and Eritrea. Carlsberg Academy, Copenhagen. Biol Skr. 54

Geist HJ, Lambin EF (2001) What drives tropical deforestation? A meta-analysis of proximate and underlying causes of deforestation based on subnational case study evidence. LUCC report series 4. Louvain-la-Neuve, Belgium

Goudie A (2006) The human impact on the natural environment: past, present and future, 6th edn. Blackwell Publishing, Oxford

Hall FC (2001) Ground-based photographic monitoring. Pacific Northwest Research Station, Portland

Harsch MA, Hulme PE, McGlone MS, Duncan RP (2009) Are treelines advancing? A global meta-analysis of treeline response to climate warming. Ecol Lett 12:1040–1049. doi:10.1111/j.1461-0248.2009.01355.x

Hendrickx H, Jacob M, Frankl A, Guyassa E, Nyssen J (2015) Quaternary glacial and periglacial processes in the Ethiopian highlands in relation to the current afro-alpine vegetation. Z Geomorphol 59:37–57. doi:10.1127/0372-8854/2014/0128

Holtmeier FK, Broll G (2005) Sensitivity and response of northern hemisphere altitudinal and polar treelines to environmental change at landscape and local scales. Glob Ecol Biogeogr 14:395–410. doi:10.1111/j.1466-822X.2005.00168.x

Holtmeier FK, Broll G (2007) Treeline advance—driving processes and adverse factors. Landsc Online 1:1–32. doi:10.3097/LO.200701

Houghton R (1994) The worldwide extent of land-use change. Bioscience 44:305–313. doi:10.2307/1312380

Hurni H (1988) Degradation and conservation of the resources in the Ethiopian highlands. Mt Res Dev 8:123–130. doi:10.2307/3673438

Hurni H (2005) Decentralised development in remote areas of the Simen Mountains, Ethiopia. Dialogue series of the NCCR North-South 45.

Hurni H (2015) Paleoglaciated landscapes in Simen and other high-mountain areas of Ethiopia. In: Billi P (ed) Landscapes and landforms of Ethiopia. Springer, Dordrecht, pp 139–146

Hurni H, Stähli P (1982) Simen Mountains, Ethiopia Vol II: Climate and the dynamics of altitudinal belts from the last cold period to the present day. Geographische Gesellschaft Bern und Geographica Bernensia 7, Bern, Switzerland

Jacob M, Annys S, Frankl A, Beeckman H, Guyassa E, Nyssen J (2015) Treeline dynamics in the tropical African highlands—identifying drivers and dynamics. J Veg Sci 26:9–20. doi:10.1111/jvs.12215

Keiner M (2000) Towards a new management plan for the Simen Mountains National Park. Institut für Raum-und Landschaftsentwicklung, Zürich

Kieffer B, Arndt N, Lapierre H, Bastien F, Bosch D, Pecher A, Yirgu G, Ayalew D, Weis D, Jerram D, Keller F, Meugniot C (2004) Flood and shield basalts from Ethiopia: magmas from the African superswell. J Petrol 45:793–834. doi:10.1093/petrology/egg112

Klötzli F (1958) Zur Pflanzensoziologie des Südhanges der Alpinen Stufe des Kilimandscharo, Berichte des Geobotanischen Institutes

Körner C, Paulsen J (2004) A world-wide study of high altitude treeline temperatures. J Biogeogr 31:713–732. doi:10.1111/j.1365-2699.2003.01043.x

Lambin EF (1997) Modelling and monitoring land-cover change processes in tropical regions. Prog Phys Geogr 21:375–393. doi:10.1177/030913339702100303

Marino J (2003) Threatened Ethiopian wolves persist in small isolated Afroalpine enclaves. Oryx 37:62–71. doi:10.1017/S0030605303000139

Markart G, Kohl B, Perzl F (2007) Der Bergwald und seine hydrologische Wirkung—eine unterschätzte Größe? LWF Wissen 55:34–43

Masubelele M, Hoffman T, Bond J (2015) A repeat photograph analysis of long-term vegetation change in semi-arid South Africa in response to land use and climate. J Veg Sci 26:1013–1023. doi:10.1111/jvs.12303

Miehe G, Miehe S (1994) Ericaceous forests and heathlands in the Bale Mountains of South Ethopia—ecology and man's impact. Stiftung Walderhaltung in Afrika, Hamburg

Mugagga F, Kakembo V, Buyinza M (2012) Land use changes on the slopes of Mount Elgon and the implications for the occurrence of landslides. Catena 90:39–46. doi:10.1016/j.catena.2011.11.004

Nievergelt B, Good T, Güttinger R (1998) A survey of the flora and fauna of the Simen Mountains National Park. Walia (special issue), Zürich

Nyssen J, Descheemaeker K, Zenebe A, Poesen J, Deckers J, Haile M (2009a) Transhumance in the Tigray Highlands (Ethiopia). Mt Res Dev 29:255–264. doi:10.1659/mrd.00033

Nyssen J, Haile M, Naudts J, Munro N, Poesen J, Moeyersons J, Frankl A, Deckers J, Pankhurst R (2009b) Desertification? Northern Ethiopia re-photographed after 140 years. Sci Total Environ 407:2749–2755. doi:10.1016/j.scitotenv.2008.12.016

Nyssen J, Frankl A, Haile M, Hurni H, Descheemaeker K, Crummey D, Ritler A, Portner B, Nievergelt B, Moeyersons J, Munro N, Deckers J, Billi P, Poesen J (2014a) Environmental conditions and human drivers for changes to north Ethiopian mountain landscapes over 145 years. Sci Total Environ 485–486:164–179. doi:10.1016/j.scitotenv.2014.03.052

Nyssen J, Van den Branden J, Frankl A, Van de Velde L, Billi P (2014b) Twentieth century land resilience in Montenegro and consequent hydrological response. Land Degrad Dev 349:336–349. doi:10.1002/ldr.2143

Peyron O, Jolly D, Bonnefille R, Vincens A, Guiot J (2000) Climate of East Africa 6000 14C Yr B.P. as Inferred from Pollen Data. Quat Res 54:90–101. doi:10.1006/qres.2000.2136

Pickard J (2002) Assessing vegetation change over a century using repeat photography. Aust J Bot 50:409–414. doi:10.1071/BT01053

Roush W, Munroe JS, Fagre DB (2007) Development of a spatial analysis method using ground-based repeat photography to detect changes in the alpine treeline ecotone, Glacier National Park, Montana, U.S.A. Arct Antarct Alp Res 39:297–308. doi:10.1657/1523-0430(2007)39[297:DOASAM]2.0.CO;2

Sebald O (1968) Bericht über botanische Studien und Sammlungen am Tana-See und im Semyen-Gebirge (Äthiopien). Ergebnisse der botanischen Reise Oskar Sebald im Jahre 1966 nach Äthiopien 2.Stuttgarter Beitr Naturk 194

Soini E (2005) Land use change patterns and livelihood dynamics on the slopes of Mt. Kilimanjaro, Tanzania. Agric Syst 85:306–323. doi:10.1016/j.agsy.2005.06.013

Spehn EM, Liberman M, Körner C (2006) Land use change and mountain biodiversity. CRC Press, Boca Raton

Tadege A (2007) The federal democratic republic of Ethiopia Climate Change National Adaptation Programme of Action (NAPA). National Meteorological Agency, Addis Ababa, Ethiopia

Tegene B (2002) Land-cover/land-use changes in the derekolli catchment of the South Welo Zone of the Amhara Region, Ethiopia. East Afr Soc Sci Res Rev 18:1–20. doi:10.1353/eas.2002.0005

Tekle K, Hedlund L (2000) Land cover changes between 1958 and 1986 in Kalu District, Southern Wello, Ethiopia. Mt Res Dev 20:42–51. doi:10.1659/0276-4741(2000)020[0042:LCCBAI]2.0.CO;2

Umer M, Lamb H, Bonnefille R, Lézine A, Tiercelin J, Gibert E, Cazet J, Watrin J (2007) Late Pleistocene and Holocene vegetation history of the Bale Mountains, Ethiopia. Quat Sci Rev 26:2229–2246. doi:10.1016/j.quascirev.2007.05.004

Van Bogaert R, Haneca K, Hoogesteger J, Jonasson C, De Dapper M, Callaghan TV (2011) A century of tree line changes in sub-Arctic Sweden shows local and regional variability and only a minor influence of 20th century climate warming. J Biogeogr 38:907–921. doi:10.1111/j.1365-2699.2010.02453.x

Webb RH, Boyer DE, Turner RM (2010) Repeat photography: methods and applications in the natural sciences. Island Press, Washington

Wondie M, Schneider W, Melesse AM, Teketay D (2011) Spatial and temporal land cover changes in the Simen Mountains National Park, a World Heritage Site in Northwestern Ethiopia. Remote Sens 3:752–766. doi:10.3390/rs3040752

Yanda P, Shishira E (2001) Forestry conservation and resource utilisation on the southern slopes of Mount Kilimanjaro: trends, conflicts and resolutions. In: Ngana J (ed) Water resources management in the Pangani River Basin: challenges and opportunities. Dar es Salaam university Press, Dar es Salaam, pp 104–117

Yihune M, Bekele A, Tefera Z (2009) Human-wildlife conflict in and around the Simen Mountains National Park, Ethiopia. Ethiop J Sci 32:57–64

Zeleke G, Hurni H (2001) Implications of land use and land cover dynamics for mountain resource degradation in the Northwestern Ethiopian highlands. Mt Res Dev 21:184–191. doi:10.1659/0276-4741(2001)021[0184:IOLUAL]2.0.CO;2