Treeline dynamics and forest cover change in afro-alpine Ethiopia, as affected by climate change and anthropo-zoogenic impacts

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2015

Cover: *Erica arborea* L. forest at the northern slope of Lib Amba Mountain (3993 m a.s.l.) part of the Abune Yosef Mountain range, with in the background the treeline at approx. 3700 m a.s.l. Photograph taken by Miró Jacob on 3 November 2014.

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Prof. dr. Jan Nyssen, Department of Geography, Physical Geography, Ghent University, Belgium

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Rector: Prof. dr. Anne De Paepe

In the highlands of Ethiopia
There is a forest for poverty to shelter under

Modified from 'A tree for poverty'
(from a Somali gabei)

Laurence, M. 1993. A tree for poverty.
Library Press, and ECW Press. Ontario, USA.

Acknowledgment

This journey has carried me to the highest peaks of North Ethiopia along a breath-taking route, which I only completed thanks to the help of many persons and institutions.

I would like to express my sincerest gratitude to my promoter Prof. dr. Jan Nyssen. Jan gave me the opportunity to explore the afro-alpine forests of the Ethiopian highlands, guided me in the field, motivated me with his enthusiasm and shared many ideas during the past four years. I am also very grateful to my second promoter Hans Beeckman for initiating me into the new world of wood biology, providing me with useful insights and for motivating me to invest in this valuable part of the research.

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Last but not least, I wish to thank Silke for her help and support from start to finish. Thanks for bringing out the best of me!

List of Abbreviations

AA	Afro-alpine Belt
AFG	Avalanche Fed Glacier
AGRG	Applied Geomatic Research Group
ANOVA	Analysis of Variance
AP	Aerial Photograph
AY	Abune Yosef
BA	Basal Area
CAM	Crassulacean Acid Metabolism
CC	Canopy Cover
CI	Confidence Interval
CV	Coefficient of Variation
DEM	Digital Elevation Model
DH	Dominant Height
EB	Ericaceous Belt
$\mathbf{E_{corr}}$	Corrected Energy received
ELA	Equilibrium Line Altitude
EMA	Ethiopian Mapping Agency
EPRDF	Ethiopian People’s Revolutionary Democratic Front
EWCA	Ethiopian Wildlife Conservation Authority
FA	Ferrah Amba
FAO	Food and Agriculture Organization
FEWS	Famine Early Warning System
FI	Flatness Index
GCP	Ground Control Points
GNSS	Global Navigation Satellite System
GST	Ground Surface Temperature
GT	Ground Truth
HDC	Height Diameter Coefficient
IPCC	Intergovernmental Panel on Climate Change

ITCZ	Intertropical Convergence Zone
IUCN	International Union for Conservation of Nature
LA	Lib Amba
LGM	Last Glacial Maximum
LM	Linear Model
LUC	Land Use and Land Cover
MAE	Mean Absolute Error
MAF	Moist evergreen Afromontane Forest
MMU	Minimum Mapable Unit
MR	Mean Rainfall
MS	Meteorological Station
MT	Mean Temperature
NAPA	National Adaptation Programme of Action
ND	No Data
NMA	National Meteorological Agency
NOAA-CPC	National Oceanic and Atmospheric Administration - Climate Prediction Centre
PCA	Principal Component Analysis
QMD	Quadratic Mean Diameter
RFE	Rainfall Estimates
RLM	Robust Linear Model
RMSE	Root Mean Square Error
SMNP	Simen Mountains National Park
SRTM	Shuttle Radar Topography Mission
ST	Soil Temperature
SWC	Soil and Water Conservation
TH	Top Height
TLCR	Tree Live Crown Ratio
TLU	Tropical Livestock Unit
TPH	Trees per Hectare
UNCED	United Nations Conference on Environment and Development
UNEP-WCMC	United Nations Environment Programme - World Conservation Monitoring Centre
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
VC	Vegetation Cover
WV	Woody Vegetation

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Chapter 1 General introduction

1.1 Problem statement

Mountain environments are among the most sensitive ecosystems worldwide (Price and Egan, 2014) and at the same time regionally and globally important for their ecological, socioeconomic and aesthetic values (Schild, 2008). Mountains occupy, according to the United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC) definition, 23% of the global land surface and are home to 20% of the world's population, of which a high proportion economically vulnerable people (Körner and Ohsawa, 2005; Schild, 2008). The main ecosystem services of mountains are threefold: provisioning services, regulating and supporting services, and cultural services (Körner and Ohsawa, 2005). Each of these ecosystem services make specific contributions to the vulnerable balance between the mountain environment and the local and global communities. Mountain vegetation and soils are important for the reduction and mitigation of natural hazards (IPCC, 2007). Mountains also play a key role in the water cycle. The water holding capacity of mountain forests is very important for this hydrological balance (Körner and Ohsawa, 2005). 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).

At present, the fragile mountain environments are subjected to a range of biophysical and socioeconomic drivers of change, including climate change. Disturbance of the environmental balance threatens the ecosystem services of mountains and exposes mountain communities and lowland communities to biophysical and socioeconomic risks. Over the past decade, the interaction between the environment and man made changes is rapidly risen on the international political agenda, with a main focus on climate change. Mountains started to receive attention during the 1992 United Nations Conference on Environment and Development (UNCED) with a specific chapter and there was even a Mountain Summit in Bishkek in 2002. But despite this growing awareness of the importance of mountains, mountain environments remain marginalized in the global development agendas (Schild, 2008).

In particular, relatively little is known about the tropical African highlands and mountain forests. The tropical mountain forests of Africa with their woody and epiphytic biomass are important for slope stability and regionally important as a hygric buffer (Miehe and Miehe, 1994; Price, 2003). These mountain forests play a key role in 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). Ecosystem stability in the highlands is a requisite for erosion control, catchment quality and biological richness (Spehn and Liberman, 2006). The ecology and richness of the highland vegetation plays a vital role for clean and steady water discharge. 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 and Liberman, 2006). Endemic species richness is particularly high in the North Ethiopian highlands. The endangered Walia ibex (*Capra walie*) forms a striking well known example, threatened by habitat destruction (Gebremedhin, 2010).

Improved knowledge about the vulnerable tropical African mountain forests is also important in a global context of climate warming. The global average temperature has risen during the past century, a change that is most prominent and rapid at high altitudes and latitudes (Harsch et al., 2009). The upper limit of the tropical highland forests are temperature sensitive and thus potentially responsive to climate warming (Holtmeier and Broll, 2007). Mountain treeline ecotones represent an important ecological boundary marked by an apparent transition from closed to treeless alpine vegetation (Holtmeier, 2009). There are a growing number of studies about treeline dynamics in the tropics (e.g. Bader, 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 to treeline dynamics at higher northern latitudes (Figure 1.1) (Holtmeier and Broll, 2007).

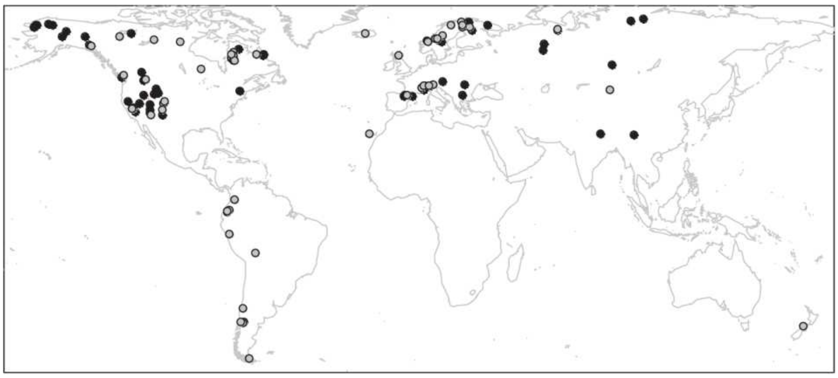

Figure 1.1 This map is part of a global meta-analysis of treeline dynamics by Harsch et al. (2009). Black circles are advancing and grey circles are not advancing treelines (Harsch et al. 2009). At the same time, the distribution of the treeline sites also illustrates the scarcity of treeline studies in the southern hemisphere – particularly on the African continent.

However, all changes to the treeline cannot be ascribed to climate change only, as tropical mountains are densely populated: 135 inhabitants per km² in areas above 2500 m in Ethiopia (Huddleston et al., 2003). Humans directly impact the upper treeline through livestock herding, fire and wood harvesting. This affects the vulnerable mountain environment, due to the loss and fragmentation of tropical mountain forests.

Little is known about the treeline history in tropical Africa. Some local observations in the North Ethiopian highlands indicate a shift of the treeline. Nievergelt et al. (1998) stated that the treeline raised at the eastern slope of the Jinbar River and at the slopes of Inatye mountain, but gives no indication of the scale of this process. Hurni (2005) repeated historical terrestrial photographs from the Rosen expedition in 1905. These unique repeat photographs span a period of 100 years of landscape changes. In two photographs of the Silki Mountains the treeline is observed to have been risen with 100-200 m, reaching 3850 m a.s.l. (Figure 1.2). Hurni (2005) explains this shift of the treeline as potentially induced by global warming, but gives no further evidence. Until today, the question whether climate change is a driver of treeline dynamics in the North Ethiopian highlands remains unanswered.

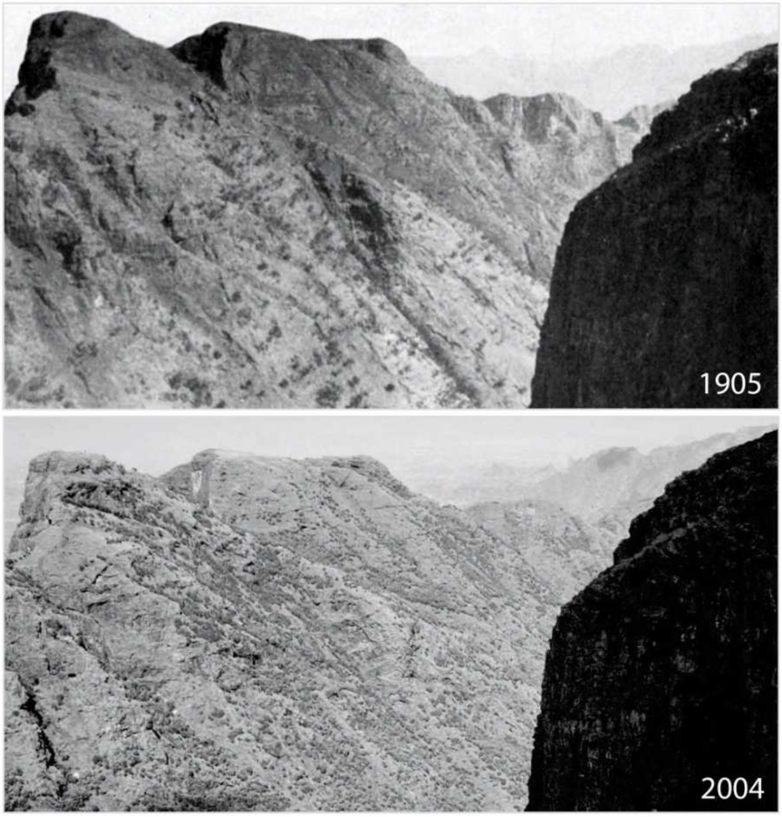

Figure 1.2 Repeat photograph from Hurni (2005) taken from above Kosso Village looking towards the Silki Mountains. These photographs indicate a natural regrowth of the *Erica* forest and an upwards shift of the upper treeline by 100-200 m. The upper photograph is taken by the Rosen expedition in 1905 and the lower repeat photograph is taken by Hurni in 2004.

1.2 Thesis objectives and research questions

The main objective of this thesis is to provide a better understanding of mountain forest cover changes and treeline dynamics in the North Ethiopian highlands since the mid-20th century.

In this formulation of the objective, ‘a better understanding’ refers to:

- identifying spatiotemporal forest cover change patterns in the North Ethiopian mountains
- identifying treeline dynamics in the North Ethiopian mountains
- identifying the drivers of these changes

It is aimed that this improved understanding of tropical highland forests contributes to sustainable forest management and enhances water infiltration, reduces land degradation and improves biological richness in the North Ethiopian highlands.

Overall points of action undertaken to achieve the main objective were:

- to compile a large dataset of aerial and terrestrial photographs of the North Ethiopian mountains
- to assemble a network of meteorological measurements
- to monitor soil temperature
- to acquire stem disks, increment cores and tree measurements from forest plots and transects
- to quantify land use and land cover change
- to quantify treeline dynamics

1.2.1 Research questions

The two key research questions of the thesis may arise as:

- *Are treelines in the tropical African highlands rising due to climate change?*
- *How did the high altitude African tropical forests change over the last 50 years?*

These core questions can be subdivided in a number of sub-questions addressed in the individual chapters:

- *Are treelines in tropical Africa rising? (Chapter 2)*

- *Can we use periglacial depositis to reconstruct paleoclimatic conditions in the North Ethiopian Highlands? (Chapter 3)*
- *What is the effect of protection on the physiognomy of the afro-alpine Erica arborea forest? (Chapter 4)*
- *Are the afromontane and afro-alpine forests decreasing over the past half century? (Chapter 5 and 10)*
- *Did the establishment of the National Park in the Simen Mountains affect forest cover? (Chapter 6)*
- *Can we use RFE to estimate rainfall dynamics in the tropical African highlands? (Chapter 7)*
- *How do microclimatic conditions influence Erica arborea tree growth at the treeline in the North Ethiopian highlands? (Chapter 8)*
- *Is Erica arborea growth responsive to climate variability? (Chapter 9)*
- *How did land use patters affect vegetation cover in the North Ethiopian highlands? (Chapter 10)*

1.3 Definitions

A recent study about the definition of forests on a global scale indicated that there are more than 800 different definitions for forests and wooded areas (UNEP et al., 2009). According to the Food and Agriculture Organization (FAO) definition, a forest should cover a minimum area of 0.5 ha with trees of minimum 5 m in height and a crown cover of more than 10 percent (FRA, 2015). Within the United Nations Framework Convention on Climate Change (UNFCCC), the definition of forest is more flexible. The threshold values for a forest lie within a minimum range of 0.01-1.0 ha, 2-5 m tree height and 10-30 percent crown cover (UNEP et al., 2009). With the purpose of identifying the vulnerable mountain forests, the minimum limit of the UNFCCC is used as reference for forests.

The treeline is located at the upper limit of the forest. In the Oxford Dictionnary of Plant Sciences (2013), a treeline is defined as “a line through the last of the stunted trees, forming the latitudinal or altitudinal limit beyond which the climate is too cold for trees to grow”. The treeline can thus be associated with a climate limit. However, many authors have attempted to define the treeline; an overview is given by Callaghan et al. (2002) and Holtmeier (2009). The terminology is mainly dependent on the region of interest of the authors. Forestry scientists are interested in the forest limit, while ecologists are more concerned about the species limit (Callaghan et al., 2002). The shift from uppermost closed montane forests to treeless alpine vegetation is clearly marked by the shift in vegetation height (Körner and Paulsen, 2004). But, it is only when observed from a great distance that the treeline may appear as an abrupt boundary. In reality there is a steep gradient from closed forest to shrub-only treeless montane vegetation stages, characterized by increasing stand fragmentation and stuntedness (Figure 1.3) (Körner and Paulsen, 2004; Van Bogaert et al., 2011). This transition is called the treeline ecotone (or *kampfzone*) (Figure 1.3). The treeline location is thus not exactly identifiable and must be defined in conventions (Armand, 1992).

There are three frequently used terminologies: (i) 'timberline' (ii) 'tree species line' and (iii) 'treeline'; which refer to the transition from forest to non-forest stages (Figure 1.3). These widely used and often incorrectly mixed terms are described by Körner (1998). (i) The timberline (or *waldgrenze*) is the boundary of the closed forest. Although commonly used, this is not a clearly defined term (Figure 1.3). (ii) The tree species line (or *baumgrenze*) is the boundary formed by the upper individuals of the tree species, regardless of the growth form (Figure 1.3). (iii) The treeline or forestline is formed by the connection of the highest forest patches in an area. These patches consist of groups of trees characterized by a growth height of more than three meter (Figure 1.3). The physiognomic treeline (30% tree cover) is used in this study to refer to the forestry limit of the continuous forest (Van Bogaert et al., 2011). Minimum tree height is commonly used as a criterion to define a tree, however cautiousness is advised as this height can differ between species and authors (Holtmeier, 2009). There is scientific agreement to define a tree as an upright woody plant with a height of at least 3 m (Körner, 1998). But this tree height-limit is linked with seasonal snow cover, which is not the case in the tropical mountains. *Erica arborea* L. trees at the treeline form multi-stemmed stunted growth forms, these are also known as "dwarf forests" (Miehe and Miehe, 1994). Although smaller than the FAO definition, these scrub-sized trees are considered part of the upper forest (Brass, 1964).

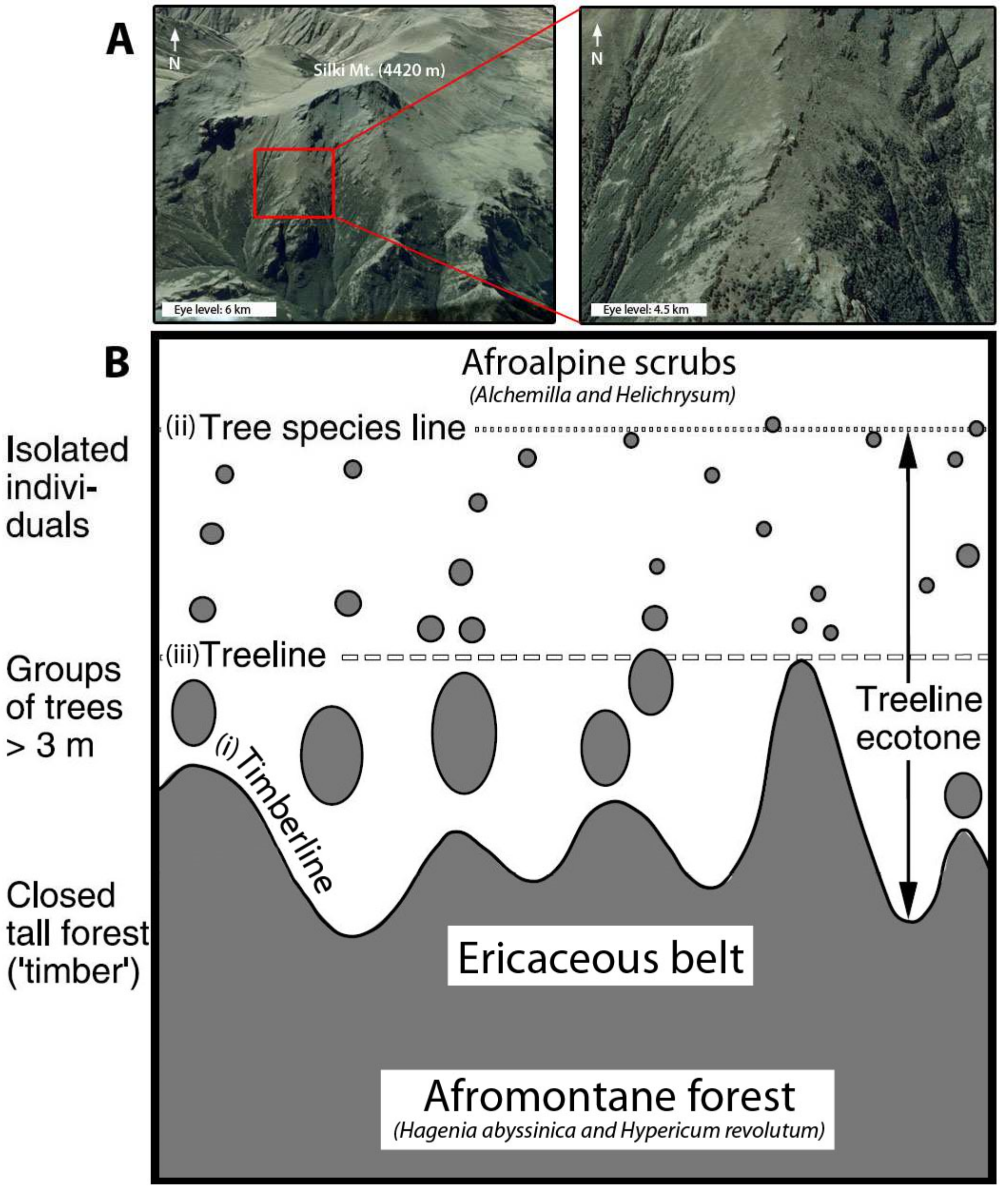

Figure 1.3 Complexity of the treeline (a) Google Earth Image of the treeline at the Simen Mountains, Silki Mountain (13°20’N, 38°15’E; 4420 m a.s.l.), visualized at two different scales to emphasize the treeline gradient. (b) The treeline ecotone, modified after Körner and Paulsen (2004), with distinction between timberline, treeline and tree species line.

The ericaceous trees that form the upper treeline forest in the tropical African mountains show an inverse relation between tree height and altitude (Wesche et al., 2000). The ericaceous belt of the African highlands is situated in between the upper montane forests with *Juniperus, Hagenia abyssinica* and *Hypericum revolutum* and the lower afro-alpine scrubs of *Alchemilla* and *Helichrysum* (Figure 1.3) (Bussmann, 2006).

1.4 Study area

The Ethiopian highlands comprise about 50 percent of the mountains of Africa above 2000 m. These highlands result from a rapid epeirogenic Tertiary uplift that started some 45 million years ago, which was accompanied by volcanism and faulting in the Late Tertiary and Pleistocene (Kieffer et al., 2004). The high plateaus of Ethiopia are formed by stratified basalt series of over 2000 m thick, covering subhorizontal Paleozoic and Mesozoic sedimentary rocks (Bussert, 2010). In the Miocene the basalt series were covered by large shield volcanoes, currently deeply eroded (Kieffer et al., 2004). This elevated topography provided Ethiopia with the nickname “Roof of Africa”. Consequently, these highlands form a good context to study mountainous forests and treeline dynamics. The study area consists of three mountain ranges in the North Ethiopian highlands (Figure 1.4). The Simen Mts. (13°16’N, 38°24’E, 4540 m a.s.l.) home to the highest peak of Ethiopia (Ras Dejen Mt.); Lib Amba Mt. (12°04’N, 39°22’E, 3993 m a.s.l.) of the Abune Yosef Mts.; and Ferrah Amba Mt. (12°52’N, 39°30’E, 3939 m a.s.l.). These three mountains are peaking above the present ericaceous belt between 3200 and 3700 m a.s.l.

The study area will be presented in detail at the beginning of every chapter.

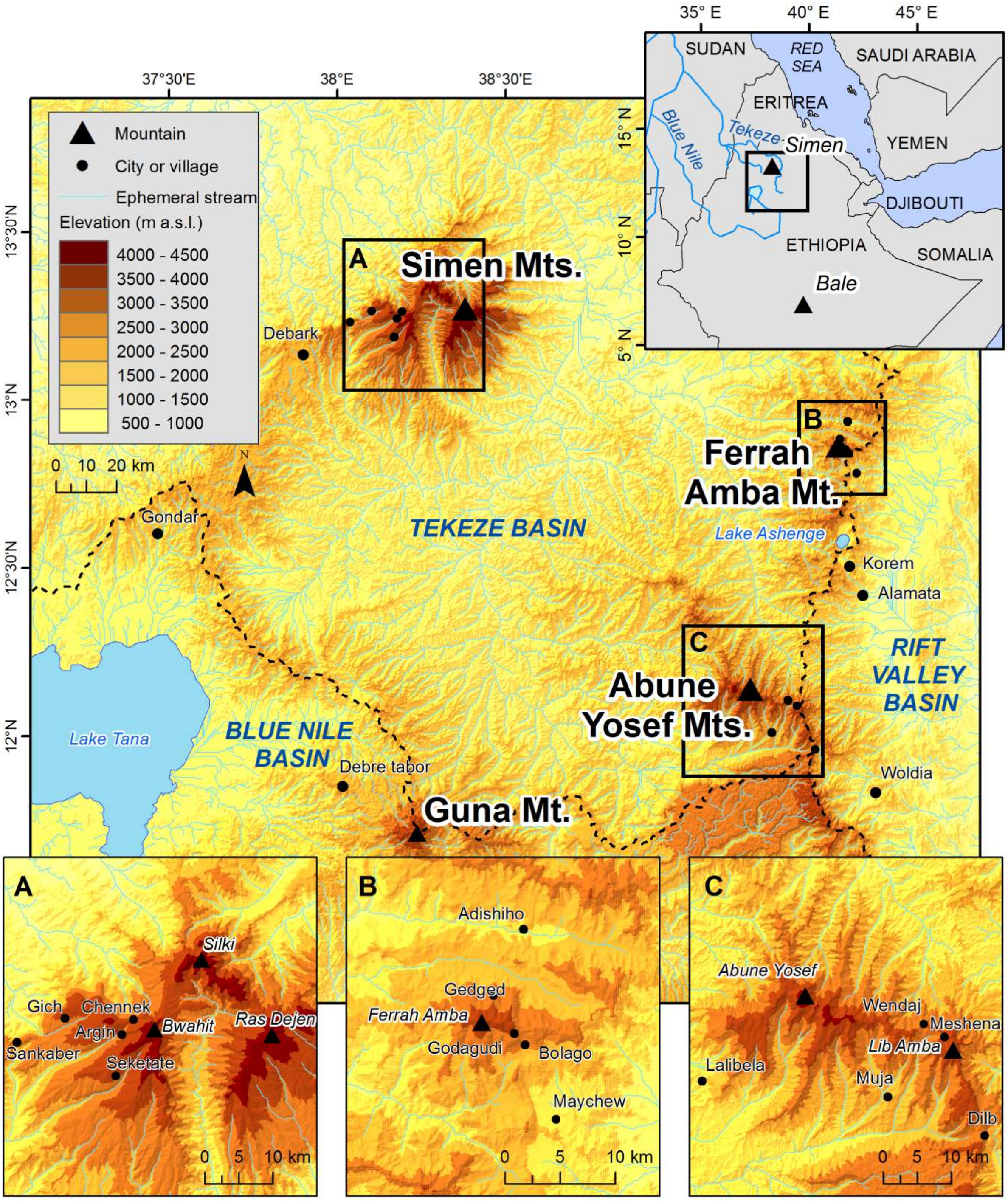

Figure 1.4 Location of the three main study areas considered in this thesis.

1.5 Thesis outline

The present chapter is the first chapter and is a general introduction to the thesis. The following chapters of the thesis are subdivided in four main parts (Figure 1.5).

In Part 1, the state of the art about treeline dynamics and the environmental setting of the study area are presented in three chapters. In Chapter 2, the current knowledge about treeline dynamics and its drivers are reviewed at the scale of tropical Africa. In the following two chapters, we zoom to the environmental setting of the study area in the North Ethiopian highlands. In Chapter 3, the geomorphological setting and paleoclimatologic significance of the study area is described in detail and presented in a geomorphological map and in Chapter 4 the physiognomy of the afro-alpine forests in the North Ethiopian highlands are described.

Forest cover change and treeline dynamics and their drivers in the North Ethiopian highlands are addressed in Part 2 and 3. Part 2 consists of two detailed studies of forest cover change and treeline dynamics. In these studies, aerial and terrestrial photographs and satellite imagery are used to map forest cover and treeline changes in respectively Lib Amba Mt. (Chapter 5) and the Simen Mts. (Chapter 6). The drivers of change are assessed in Part 3 using multidisciplinary methodologies. The first three chapters study the climate effect on tree growth and on the treeline. In Chapter 7, satellite derived Rainfall Estimates are evaluated as a tool to study spatiotemporal rainfall patterns in the North Ethiopian highlands. In Chapter 8, meteorological measurements are used to characterize the prevailing mountain climate conditions and to evaluate the climate effect on the treeline and in Chapter 9 the climate response of tree growth is studied by wood anatomy and dendrochronology. In the final chapter of Part 3 (Chapter 10), the impact of land use and land cover changes on the mountain forest are studied.

In the general discussion and conclusion of Part 4, a comprehensive conceptual model is provided. This model includes land management recommendations for a sustainable rehabilitation of the mountain forests and their ecosystem services of the North Ethiopian highlands.

I have completed data collection, analysis and interpretation, together with the bulk of the writing in all chapters, except for chapter 3 and partly for chapter 10. In chapter 3, published by Hanne Hendrickx, I contributed at all stages, inclusively during the fieldwork in Ethiopia, while the majority of the work was done by Hanne. Chapter 10 is based on the master dissertation of Liên Romeyns, but I am the first author of this article-based chapter, since I did the bulk of the writing and advised Liên at all stages in her dissertation.

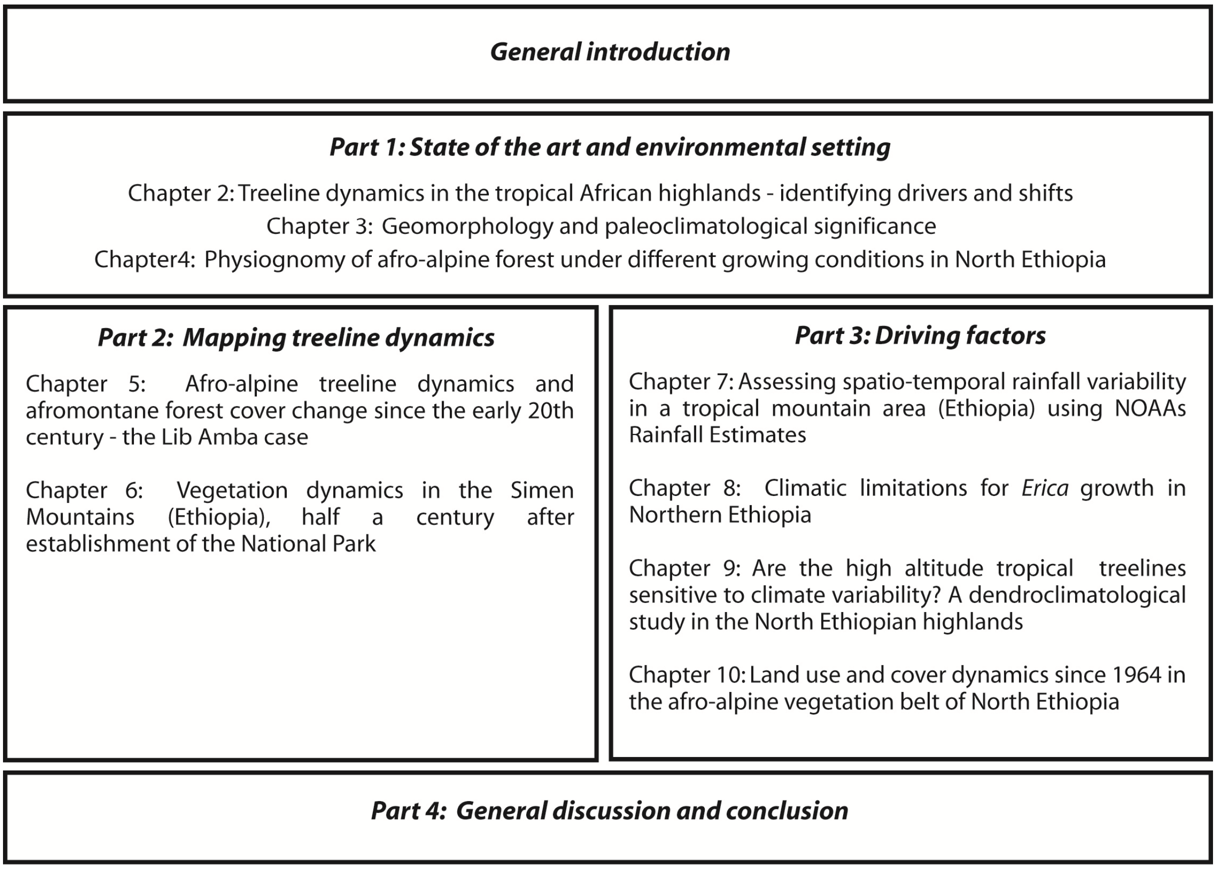

Figure 1.5 Outline of the thesis

1.6 Publications

Master dissertations framing within the PhD Research

Hendrickx, H. (2014) Geomorphological mapping with focus on glacial and periglacial processes in the North Ethiopian Highlands in relation to the afro-alpine vegetation. Unpub. Master thesis, Department of Geography, Ghent University.

Romeyns, L. (2014) The effect of land use and cover changes on gully dynamics in Northern Ethiopia's afro-alpine areas. Unpub. Master thesis, Department of Geography, Ghent University.

A1 - International publications in journals indexed in the ISI Web of Science

Hendrickx, H., **Jacob, M.**, Frankl, A., Etefa Guyassa, Nyssen, J. (2015). Quaternary glacial and periglacial processes in the Ethiopian Highlands in relation to the current afro-alpine vegetation. Zeitschrift für Geomorphologie, 59 (1), 37-57.

Hendrickx, H., **Jacob, M.**, Frankl, A., Nyssen, J. (2015). Glacial and periglacial geomorphology and its paleoclimatological significance in three North Ethiopian Mountains, including a detailed Geomorphological map. Geomorphology, 246, 156-167.

Jacob, M., Frankl, A., Beeckman, H., Mesfin, G., Hendrickx, M., Guyassa, E., Nyssen, J. (2015). North Ethiopian afro-alpine treeline dynamics and forest cover change since the early 20th century. Journal of Land Degradation & Development, online early view. DOI: 10.1002/ldr.232.

Jacob, M., Romeyns, L., Frankl, A., Asfaha, T., Beeckman, H., Nyssen J. (2015). Land use and cover dynamics since 1964 in the afro-alpine vegetation belt: Lib Amba mountain North Ethiopia. Land Degradation and Development, online early view. DOI: 10.1002/ldr.2396.

Jacob, M., Annys, S., Frankl, A., De Ridder, M., Beeckman, H., Guyassa, E., Nyssen, J. (2014). Treeline dynamics in the tropical African highlands – identifying drivers and dynamics. Journal of Vegetation Science, 26 (9), 9-20.

Frankl, A., **Jacob, M.**, Haile, M., Poesen, J., Deckers, J., Nyssen, J. (2013). The effect of rainfall on the spatio-temporal variability of cropping systems and duration of the crop cover in the Northern Ethiopian Highlands. Soil Use and Management, 29(3), 374–383.

Frankl, A., Poesen, J., Scholiers, N., **Jacob, M.**, Haile, M., Deckers, J., Nyssen, J. (2013). Factors controlling the morphology and volume (V) – length (L) relations of permanent gullies in the Northern Ethiopian Highlands. Earth Surface Processes and Landforms, 38 (14), 1672-1684.

Jacob, M., Frankl, A., Mitiku, H., Zwertvaegher, A., Nyssen, J. (2013). Assessing spatiotemporal rainfall variability in a tropical mountain area (Ethiopia) using NOAAs Rainfall Estimates. International Journal of Remote Sensing, 34 (23), 8305-8321.

A1 - In review

Jacob, M., Frankl, A., Hurni, H., Lanckriet, S., De Ridder, M., Guyassa, E., Beeckman, H., Nyssen, J. (2015). Land cover dynamics in the Simen Mountains (Ethiopia), half a century after establishment of the National Park. Regional Environmental Change, in review.

Jacob, M., Frankl, A., Broidioi, S., Asfaha, T., Beeckman, H., Nyssen, J. (2015). Microclimate conditions for *Erica arborea* growth at the upper treeline in Northern Ethiopia. International Journal of Biometeorology, in review.

A4 - Publications in national journals

Nyssen, J., Lanckriet, S., Poesen, J., **Jacob, M.**, Moeyersons, J., Mitiku Haile, Frankl, A., Deckers, J. (2013). Landdegradatie in de Ethiopische hooglanden. De Aardrijkskunde, 77-95.

B - Book chapters

Nyssen, J., Poesen, J., Lanckriet, S., **Jacob, M.**, Moeyersons, J., Mitiku Haile, Nigussie Haregeweyn, Munro, N., Descheemaeker, K., Enyew Adgo, Frankl, A., Deckers, J. (2015). Land degradation in the Ethiopian highlands. In: Billi, P. (ed.), Landscapes and Landforms of Ethiopia. Dordrecht, Springer: 369-385. ISBN 978-94-017-8025-4.

C - International conference contributions (contributions as co-author are not listed)

Jacob, M., De Ridder, M., Frankl, A., Tesfaalem, A., Nyssen, J., Beeckman, H. (2015). Are the high altitude treelines of North Ethiopia sensitive to climate change? Poster presented at the Wood science underpinning tropical forest ecology and management conference, Tervuren, Belgium, May 26-29, Book of abstracts.

Jacob, M., Frankl, A., De Ridder, M., Etefa Guyassa, Beeckman, H., Nyssen, J. (2014). Can Treeline Shift in Tropical Africa be Used As Proxy to Study Climate Change? Poster presented at the American Geophysical Union (AGU), San Francisco, United States, December 15-19. Book of Abstracts, GC23E-0679.

Jacob, M., De Ridder, M., Frankl, A., Guyassa, E., Beeckman, H., Nyssen, J. (2014). Quantifying the success of improved forest management from dendrochronology: examples from North Ethiopia. Poster presented at the European Geoscience Union (EGU), Vienna, Austria, 27/04 -2/05, Book of abstracts, 16.

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Jacob, M., Frankl, A., Haile, M., Nyssen, J. (2011). Cropping systems distribution in the North Ethiopian highlands as related to spatiotemporal rainfall patterns. Poster presented at the 5th Symposium of the Ghent Africa Platform (GAPSYM5) : (r)Urban Africa multidisciplinary approaches to the African city, Ghent, Belgium, February 12, Book of abstracts, 66.

C - National conference contributions (contributions as co-author are not listed)

Jacob, M., Frankl, A., Beeckman, H., Mitiku Haile, Nyssen, J. (2013). Treeline dynamics in Afro-Alpine Ethiopia as affected by climate change and anthropo-zoogenic impacts. Poster presented at Belgian Platform for REDD+ Information (be-REDDi): Forests and Climate Change Mitigation Conference, Brussels, Belgium, November 9, Book of abstracts.

Jacob, M., Frankl, A., Kiros Meles, Hendrickx, M., Beeckman, H., De Wulf, A., Etefa Guyassa, Nyssen, J. (2013). Mapping a century of forest cover change and treeline dynamics in the North Ethiopian highlands: the Lib Amba case. Paper presented at the 5th Belgian Geographical Day, Louvain-la-Neuve, Belgium, May 24th, Book of abstracts.

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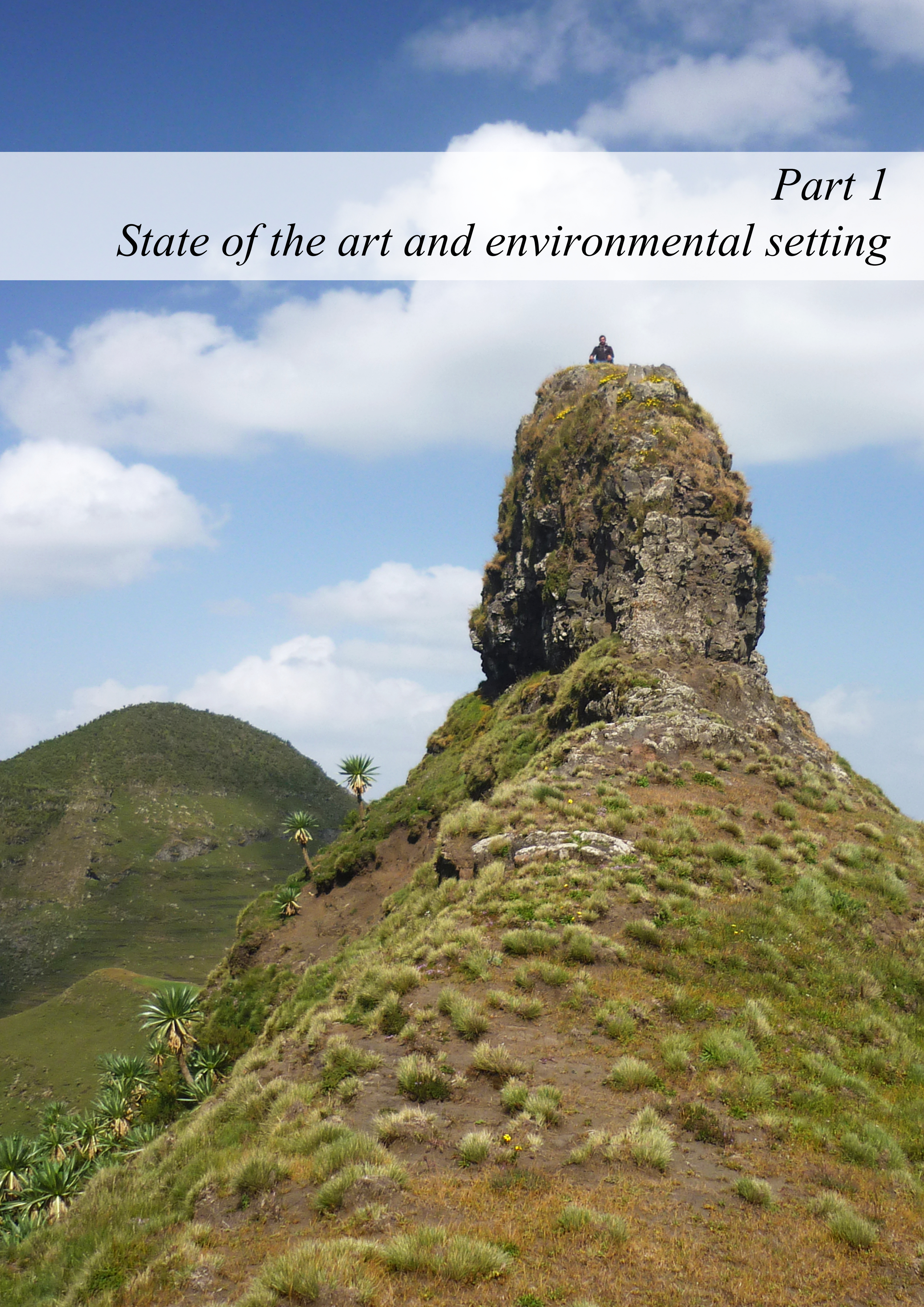
Part 1
State of the art and environmental setting



The photograph on the back of this page is taken south of Lib Amba Mountain on 23 September 2012. In front, a volcanic plug rises from the surrounding landscape with giant lobelia growing on its side. On the mountain in the back, *Erica* is growing in a protected area around the top.

Chapter 2 Treeline dynamics in the tropical African highlands: identifying drivers and shifts

This chapter is based on:

Jacob, M., Annys, S., Frankl, A., De Ridder, M., Beeckman, H., Guyassa, E., Nyssen, J. (2014). Treeline dynamics in the tropical African highlands – identifying drivers and dynamics. Journal of Vegetation Science, 26 (9), 9-20.

Abstract

High altitude forests provide important ecosystem services for the vulnerable environment of the tropical highlands. The treeline limit of these forests are temperature sensitive and thus potentially valuable as a proxy of climate change. In this study, the potential drivers of treeline change in the tropical African highlands are reviewed. The influence of climatic factors in the African tropical highlands is significantly different compared to other regions. The potentially determining factors for treeline distribution in tropical Africa are temperature, precipitation and cloudiness, carbon balance, fire and anthropo-zoogenic impacts. Despite recent temperature increase, treelines have not risen to higher altitudes in the tropical African highlands. Instead, high human pressure has caused stabilization and even recession of the treelines below their natural climatic limit, particularly through livestock herding. But, even neglecting human pressure, there might be a lag in response time between temperature and treeline change. The actual drivers of treeline change in the African tropical highlands are mainly fire and anthropogenic pressure rather than climate change. But, long-term drought periods can be a trigger for fire induced deforestation of the treeline vegetation. Additionally, in volcanic active mountains, is volcanic activity also a potentially limiting factor for the treeline distribution. Treeline dynamics can thus, in general, not be used as a proxy of climate change for the African tropical highlands.

Keywords: Anthropogenic impact; tropical afro-alpine highlands; ericaceous belt; climate change

2.1 Introduction

Alpine treelines mark the transition between mountain and alpine environments on high mountain slopes (Berdanier, 2010) and are one of the most apparent vegetation boundaries worldwide (Berdanier, 2010; Körner and Paulsen, 2004). According to Callaghan et al. (2002) and Holtmeier (2009), the shift from dense montane forests to treeless alpine grasses and shrubs is characterized by increasing stand fragmentation and stuntedness. This transition is called the treeline ecotone. Trees from the *Ericoideae* subfamily form the upper treeline forest in the tropical African mountains (Wesche et al., 2000).

The first systematic treeline studies occurred approximately 150 years ago, as reviewed in Marek (1910). At present, knowledge on the ecophysical situation of treelines in the tropics is still fragmental (Bader, 2007; Holtmeier, 2009). Tree growth is constrained by changing environmental conditions with increasing altitude (Körner, 2012). This makes the altitudinal tree-limit potentially responsive to climate change (Körner and Paulsen, 2004). This is illustrated by a lowering of the treelines in tropical Africa during the dry and cold Last Glacial Maximum (LGM) and by rising treelines in the Holocene as a result of temperature increase (Wu et al., 2007).

There are few continuous long-term climate reconstructions available that focus on the African tropics. Among the first, Thompson et al. (2002) reconstructed the Holocene climatic history in Africa from an ice core of the Kilimanjaro ice fields. Evidence was given for three periods of abrupt climatic shifts and predicted complete melting of the Kilimanjaro ice fields by 2015-2020 (Thompson et al., 2002). The IPCC (2007) stated that ‘warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level’. The temperature rise of the past century is most prominent and rapid at high altitudes and latitudes (IPCC, 2007).

The tropical African mountains are hotspots in biodiversity, comprising a high amount of endemic species that have their habitat in these mountains. A substantial reduction, shift and extinction of African flora and fauna species is expected in diverse African ecosystems (IPCC, 2007). Species that reproduce slowly, disperse poorly, and are isolated are most vulnerable to climate warming (McNeely et al., 1990). The mountain-restricted species of the African highlands are good examples of such isolated species, which are highly sensitive to environmental stress (IPCC, 2007). The value of forests on mountain slopes is much wider than only for biodiversity. High mountain forests are important for slope stability and regionally important as a hygric buffer providing water for downstream sources and for agriculture in the surrounding lowlands (Miehe and Miehe, 1994; Price, 2003). The climate controlled tree limit of these mountain forests forms a clearly visible ecotone worldwide. Afro-alpine tropical treelines are therefore considered to be a potential proxy of climate change (Bader, 2007). Evidence for this is given by LGM treeline oscillations due to past climate change in the afro-alpine mountains (Wu et al., 2007). The associated counterpart of treeline shifts are shifts in the altitudinal range of grass- and shrubland. Such shifts increase the risk of species extinctions and can impede the provision of important non-forest ecosystem services. Understanding the drivers of treeline dynamics in the tropics is important to understand dynamics and spatial patterns of vegetation at the treeline (Bader, 2007). It is important to understand the dynamics that are taking place, in order to develop sustainable conservation strategies (Burgess et al., 2007).

The aim of this paper is to identify the potential drivers of treeline change in the tropical African highlands mountains and to answer the question whether temperature sensitive treelines in these mountains are shifting as a result of climate change. This will also allow to evaluate if treeline shifts can serve as a proxy of climate change in tropical Africa.

2.1.1 Study Area

Previously studied African tropical mountains with summits ranging above the present tropical treeline elevation (3300 - 4000 m) were selected for this paper (Figure 2.1). These mountains are: Rwenzori Mountains (5109 m), Virunga Mountains (4507 m), Simen Mountains (4550 m), Bale Mountains (4377 m), Mount Elgon (4321 m), Mount Kilimanjaro (5896 m), Mount Kenya (5199 m), and Mount Cameroon (4095 m). For all these mountains, the upper treeline ecotone is formed by trees from the *Ericoideae* subfamily dominated by the genus *Erica L.* (Miehe and Miehe, 1994; Wesche et al., 2000). Treeline forests are prominent above 3000 m in most tropical African mountains and grow over an elevation range of up to 1000 m (Miehe and Miehe, 1994); described by Hedberg (1951) as the ‘ericaceous belt’. Beyond this elevation, tree growth is not possible and afro-alpine scrubs dominate in the landscape. *Erica* trees are small (up to 8 m) and have needle-like scleromorphic leaves. Afro-alpine scrubs are dominated by species of *Alchemilla* and *Helichrysum* (Bussmann, 2006). Anthropo-zoogenic impact strongly modified the vertical extent of the ericaceous belt by woodcutting, fire and grazing. But despite the limited area still covered by ericaceous forest at the high altitude tree limit, this forest type remains vital for the regional environment of the tropical African highlands (Miehe and Miehe, 1994).

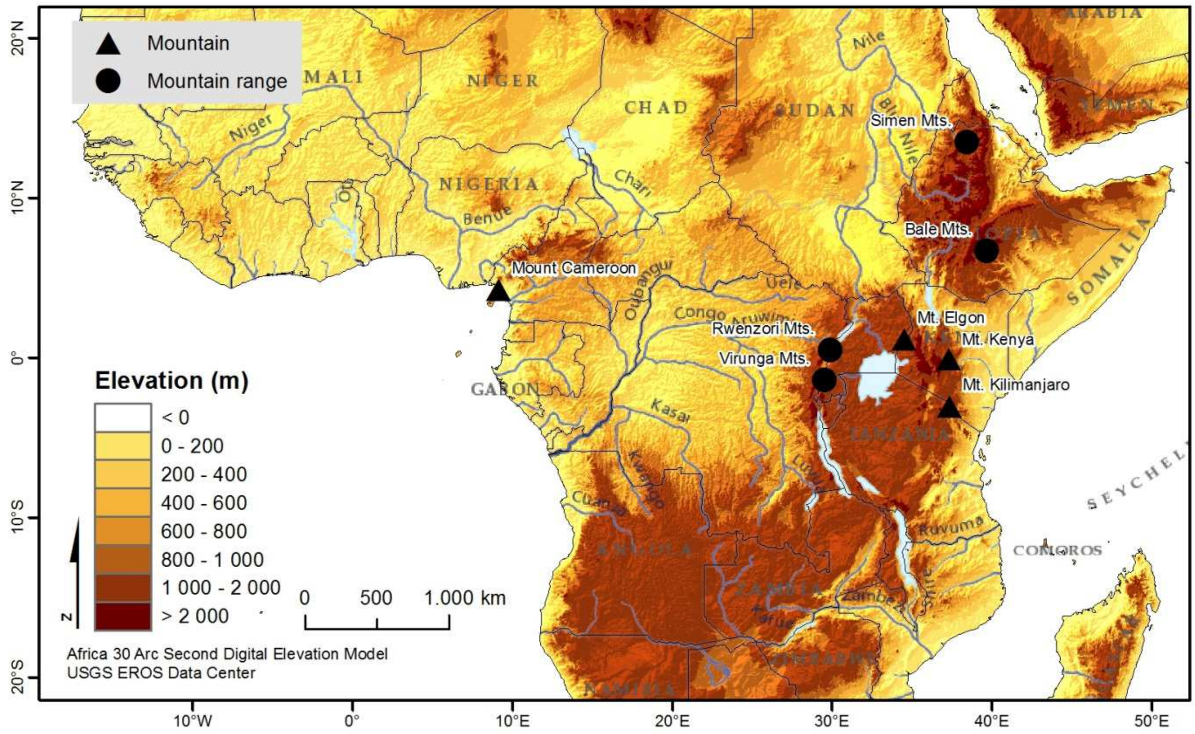


Figure 2.1 The studied tropical mountains of Africa that range above the treeline elevation.

2.2 Biophysical and anthropo-zoogenic constraints for tree growth in the tropical African highlands

The elevation of the treeline is limited by local and global environmental and anthropo-zoogenic constraints, which cause trees to reach their limit at a certain elevation and prevent tree growth above that limit (Körner, 2012; Wieser and Tausz, 2007). The biological limit is caused by severe habitat stress, which is limiting metabolism, development and reproduction of the trees. At a global scale there are evident differences in the impact of these constrains between the tropical highlands and the boreal and temperate environments (Table 2.1).

Table 2.1 A comparison of potential environmental constraints for tree growth at the treeline between the tropical and the boreal and temperate zones[a]

Factor	Tropics	Boreal and temperate zone
Air temperature	Mean seasonal temperature: 5°C Diurnal fluctuation Strong solar radiation	Mean seasonal temperature: 6-8°C Length of the growing season Less strong solar radiation
Soil temperature	Diurnal variation Mean temperature: 6.7 ± 0.8°C	Seasonal variation Permafrost
Precipitation and cloudiness	High seasonal rainfall variability Cloudiness differences	Snowfall accumulation Winter desiccation
Frost damage	Lower influence: permanent adaptations	Critical factor: high influence
Carbon balance	C_3/C_4 balance	C_3 vegetation
Wind	Gentle wind: low influence	Stronger wind: high influence Snow relocation; wind-driven abrasion
Local factors	Site specific	Site specific
Anthropo-zoogenic pressure	Very high influence	Lower influence
Fire	Very high influence	Lower influence

[a] The factors are described and fully referenced in the text.

The elevation of the treeline in the tropics is determined by a combination of biophysical factors. Of which, low ambient temperature is a key factor regulating growth, regeneration and survival of trees at the treeline (Harsch et al., 2009; Holtmeier, 2009; Körner, 1998). The seasonal mean temperature at the treeline varies from 6 to 8°C outside the tropics and around 5°C in the tropics (Gehrig-Fasel et al., 2008; Körner, 2012).

The limiting factor of growth in the tropics is mainly caused by the permanent stress resulting from the pronounced temperature fluctuation between day and night (Bader, 2007; Miehe and Miehe, 1994; Wardle and Coleman, 1992). This is because high intensities of solar radiation can be reached at tropical alpine treelines during the day, due to the low latitude and high altitude, while night frost can occur during every night (Bader, 2007). Because of the tropical diurnal climate variability, it is important to differentiate the soil temperature regime in the tropics from that outside the tropics (Holtmeier, 2009). In the tropics, mean temperature should be considered a rough indicator only, since there is a large variation in site-specific temperature cycles (Miehe and Miehe, 1994). An annual mean soil temperature of 6.7 ± 0.8°C was found to correspond with the upper tree limit all year round in the tropics (Hoch and Körner, 2003).

While snowfall and snow accumulation at treeline elevations is common outside the tropics, this is rare in the tropics (Sarmiento, 1986; Smith and Young, 1987). High seasonal rainfall variability with cold, cloudy and wet seasons alternating with long droughts at the treeline are common in the African tropical highlands, both having a negative impact on tree growth at the treeline (Smith and Young, 1987). Increasing precipitation and cloudiness at the treeline elevation reduces solar radiation for photosynthesis and reduces temperatures and thus limits tree growth (Wieser and Tausz, 2007). On the other hand, water stress due to long term drought impedes seedling establishment during the growing season and reduces the resilience of the vegetation against fire (Körner, 2012). Outside the tropics, winter desiccation caused by long-term frost drought is one of the main constraints for tree growth in high mountains (Wieser and Tausz, 2007). Hygric and thermal differences caused by differences in cloudiness are considered more important as controlling factors than exposure effects for the treeline elevation in the tropics (Sarmiento, 1986).

Freezing is generally less severe and frost damage can occur all year round at the tropical treeline (Goldstein et al., 1994; Smith, 1974). Diurnal differences are especially high in the dry season, when clear skies prevail (Sarmiento, 1986). Physiological adaptations for frost resistance must therefore be permanent in tropical highlands (Sarmiento, 1986).

The partial CO_2 pressure is lower at high elevations at all latitudes. Treeline vegetation is therefore potentially responsive to increased atmospheric CO_2 pressure (Smith et al., 2009). However, Hoch and Körner (2012) studied carbon reserves of treeline trees worldwide and did not find evidence of carbon shortage. Similar results were found in single mountain ranges by Piper et al. (2006) and Shi et al. (2008). This increasingly favours the growth limit hypothesis over the traditional carbon balance hypothesis (Hoch and Körner, 2012; Simard et al., 2013). However, there is another potential effect of elevated CO_2 in the tropics, caused by the different response of C4 tropical grasses and C3 woody vegetation to elevated CO_2 pressure; C3 vegetation is competitively favoured (Ziska, 2008).

Wind speed and direction are controlled by the local topography. In general, wind speeds at treeline elevation in the tropics are lower than in extratropical mountains (Holtmeier, 2009). Evidence is given by giant groundsels and lobelias of several meters high above the treeline in the tropics (Hedberg, 1964). The influence of wind is very important to site conditions of temperate and boreal treeline ecotones; especially in the winter season when the treeline is affected by wind-driven snow relocation and abrasion by ice particles (Holtmeier, 2009). In addition there exist many local constraining factors, such as the mass elevation effect of mountain ranges or topography effects or differences caused by the soil properties.

Beside these environmental constraints, the treeline elevation is also limited by anthropo-zoogenic influences. Human induced land use and land cover changes are the main drivers of forest cover loss (Kidane et al., 2012), controlled by the continuous pressure for new farmland and firewood (Burgess et al., 2007). Based upon research in

Ethiopia (Simen and Bale Mountains) and Uganda (Rwenzori Range and Mount Elgon), Wesche et al. (2000) concluded that fire is an important factor influencing the treeline in East Africa. Natural fires are caused by lightening, but the majority of fires in tropical mountains are human-caused (Hedberg, 1964). Multiple reasons exist for human ignited fires. For example, in the Bale Mountains, fire is used to improve the grazing conditions.

Effects of herbivores on the treeline structure and position are globally observed (Cairns and Moen, 2004). The negative effects of herbivores on the treeline are primarily caused by livestock. In the agricultural system of the tropical highlands, livestock plays a key role as provider of energy, food, fertilizer and status (Nyssen et al., 2004). Livestock browsing impedes regeneration of *Erica* and other trees of the sub-alpine zone through foliage consumption, trampling and seed predation (Castro et al., 2004).

2.3 The potential drivers of treeline change

The potential drivers of treeline change are the biophysical and anthropo-zoogenic constraints, outlined above, which have recently significantly changed and thus had a potential impact on the elevation of the treeline limit.

2.3.1 Temperature increase

Hulme et al. (2001) studied air temperature patterns in Africa over the last 100 years and found that temperature in the African continent rose with 0.5°C. In the mountains of East Africa, temperature increased with 0.3°C since 1980 (Figure 2.2a). According to the A1B-scenario of the Intergovernmental Panel on Climate Change (IPCC) the temperature in the tropics will increase with 3.3°C by 2100 (IPCC, 2007). The A1B model takes into account a rapid economic growth, a global population peak in the mid-century followed by a decline, a rapid introduction of new more sustainable technologies and a switch to balanced fossil and non-fossil energy sources (IPCC, 2007). The scenarios neglecting mitigating policy actions, even project an increase of up to 4.9°C (IPCC, 2007). Vegetation belts have to adapt to these increasing temperatures, as a result temperature sensitive species may disperse to new habitats (Wright et al., 2009). In the high altitude tropical mountains, these new temperature refuges are relatively nearby and can be accessed by migration upwards the mountain until the growth limit is again reached (Wright et al., 2009).

Körner (2012) has calculated that an increase of 1°C would correspond with an increase in elevation of the treeline with 186 m. This is a general prediction on a worldwide scale, taking only temperature into account. Other factors such as the tree species sensitivity or site specific conditions (e.g. topography, inter-specific competition, moisture availability, etc.) are not included (Chambers et al., 1998; Holtmeier, 2009). The altitudinal temperature lapse rate of East Africa is 0.6°C per 100 m elevation (Peyron et al., 2000). A marked temperature increase of 0.3°C since 1980 (Hulme et al. 2001) would thus theoretically correspond with an upwards treeline shift of 50 m; and the IPCC projection of 3.3°C by 2100 with an upwards shift of 550 m (taking only temperature in account).

2.3.2 Rainfall variability

On a global scale, an average temperature rise of 5°C by 2100, would result in a drastic decrease in annual precipitation and soil moisture by 20% (Schiermeier, 2008). However, the high interannual rainfall variability makes it difficult to identify rainfall trends for Africa. According to Hulme et al. (2001), there is a relatively stable regime in East Africa with some evidence of long-term wetting. In contrast, for West Africa and the Gulf of Guinea there has been a pronounced decrease in rainfall. The scenarios of de Wit and Stankiewicz (2006) predict an increase of rainfall up to 10% and even 20% by 2100 for all tropical mountains (Figure 2.2b). Climatic wetter conditions for East Africa under global warming are predicted by most climatic models (Lanckriet et al., 2012). Hulme et al. (2001) predict a spreading trend for the equatorial zone of East Africa, where rainfall is expected to increase by 5 to 30% in December-February, but to decrease by 5 to 10% in June-August.

The impact of these changes on the treeline limit is difficult to predict. Increased rainfall and a better spread of rainfall throughout the year decreases water stress and thus enhances tree growth at the treeline. But, this will at the same time increase cloudiness and indirectly decreases the air temperature.

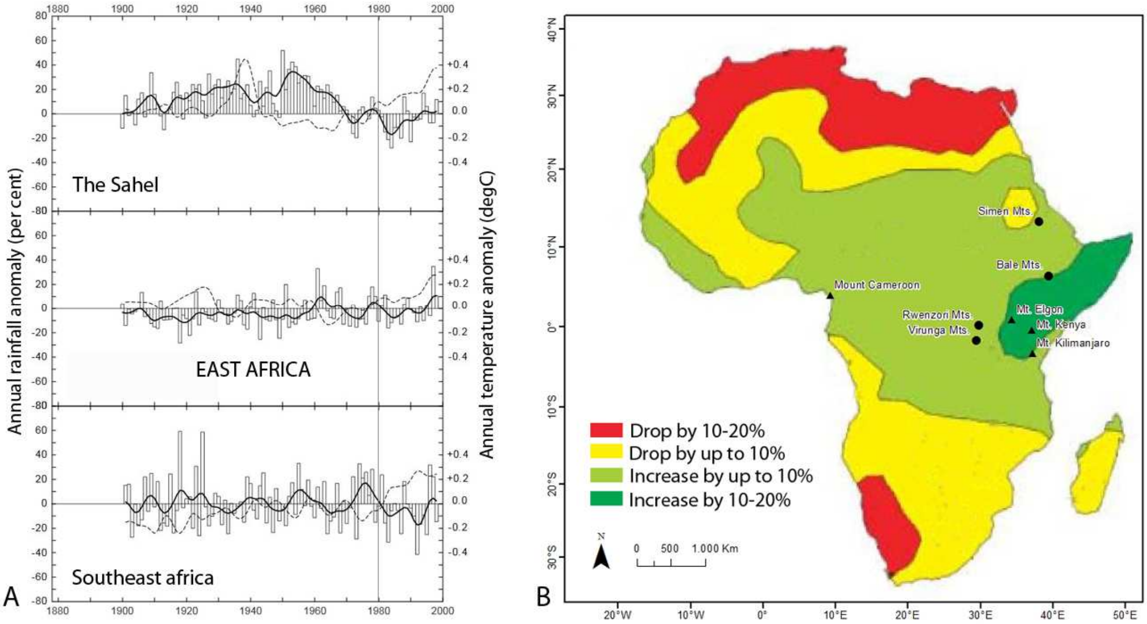


Figure 2.2 Temperature and rainfall trends in Africa since 1900 (modified after Hulme et al., (2001) and de Wit and Stankiewicz (2006)): (a) Annual rainfall (histogram and bold line) and mean temperature (dashed line) anomalies for the period 1900-1998, with the 1961-1990 average as reference. The trend is given for three African regions, of which East Africa is best corresponding with the tropical African mountain regions. Note, the temperature increase after 1980 (indicated by a vertical line); (b) expected change in precipitation by the end of the 21st century for Africa. Note, the long term wetting trend in East Africa.

2.3.3 Change in carbon balance

The atmospheric CO_2 level rose from pre-industrial 285 µmol l^{-1} (600 gigatonnes (Gt)) to the current level of 384 µmol l^{-1} (800 Gt) and is predicted to rise to 1000 Gt by 2050 (IPCC, 2007). The main focus of increased CO_2 concentrations, due to anthropogenic intensification, is on the likely effect on global mean surface temperature rise. But there are also direct effects on plant growth and physiology, independent of the climatic effect (Ziska, 2008). This effect of elevated CO_2 concentrations is different for C_3, C_4 and Crassulacean Acid Metabolism (CAM) plant species. The widespread C_3 plants and CAM plants show a significant positive response, while C_4 plants exhibit a negative response (Reddy et al., 2010). The negative effect on C_4 plants of increased CO_2 concentrations is by reduced stomatal conductance and transpiration, which causes higher leaf temperatures and increased drought stress (Bernacchi et al., 2007).

At treeline elevation in the tropics, the vegetation boundary between afro-alpine woodland and grasses correspond with the boundary between C_4 and C_3 plants, respectively. Elevated CO_2 concentrations in the tropics would thus potentially support the advance of the C_3 woody vegetation to higher elevations in competition to C_4 tropical grasses (Leakey et al., 2009). But more research is necessary for a better understanding of this different CO_2 response and the linkage with other environmental factors (Leakey et al., 2009).

2.3.4 Anthropo-zoogenic impact

The global population will grow annually with on average 1% over the period 2010-2025, which correspond to a population increase of 1.2 billion people in 15 years (UNdata, 2013). A growing proportion of the global population will be living in Africa, as the population in Africa is growing very fast (up to 3% annually) (FAO, 2007). The associated growing population and livestock pressure will further increase environmental pressure in the tropical highlands (Burgess et al., 2007). The impact is already visible through increased, wood cutting and uprooting of *Erica* stumps, inhibiting tree regeneration (Bishaw, 2001).

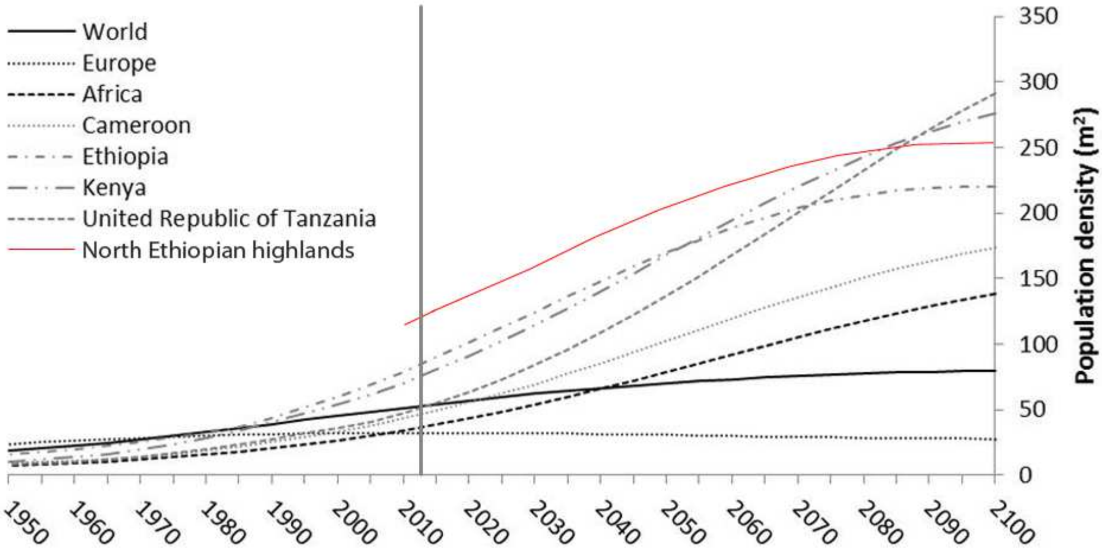


Figure 2.3 Population density dynamics in the tropical African highlands. The situation of 2013 is indicated with a vertical line. In red, the population density is plotted for areas above 3000 m a.s.l. in North Ethiopia as derived from Afripop 2010. An extrapolation to the future is made parallel to the population growth curve of Ethiopia.

2.4 Current position and dynamics of the treeline in the African tropical highlands

The potential response of treelines to climate warming is currently studied worldwide (Holtmeier and Broll, 2007). Harsch et al. (2009) analysed a global dataset of 166 treeline sites; advancing treelines were recorded in 52% of the sites and in only 1% there was a recession of the treeline. There is an association between treeline advance and temperature increase, although the mechanisms are not always straightforward. However, the analysis of Harsch et al. (2009) almost completely lacks study sites in the tropics; there are only four tropical sites included of which none are in Africa. This is because little is known about treeline dynamics in the tropical highlands of Africa (Körner, 2012). A global representation of the latitudinal position of treelines is given by Körner (1998), showing a strong relation between treeline altitude and latitude in the temperate zone and a maximum in the subtropics. But no significant changes of the treeline position with altitude over a 50° range around the equator (Körner, 1998). This graph again illustrates that treeline data is limited in the tropical and southern regions. The treeline elevation of the tropical African mountain ranges studied in this paper are therefore included in the Körner (1998) graph in Figure 2.4b; the tropical African treeline elevation is, although scattered, following the general trendline found by Körner (1998). The current understanding of treeline dynamics in Africa are compiled in an overview below and summarized in Table 2.2.

Table 2.2 Treeline dynamics and driving processes in the Tropical Highlands of Africa

Mountain range	Latitude	Elevation	Treeline[a]	Trend	Cause	Source
Simen Mountains	13°14'N	4540	4000	Upward	Climate Change and or decreased anthropogenic pressure	Hurni (2005); Wesche et al. (2000)
Bale Mountains	06°49'N	4377	4000	Downward	Anthropogenic pressure: fire	Miehe and Miehe (1994); Wesche et al. (2000)
Mount Cameroon	04°13'N	4095	3500	Downward	Volcanic activity and anthropogenic pressure	Proctor et al. (2007)
Mount Elgon	01°09'N	4321	3300	Downward	Drought pressure: fire Anthropogenic pressure	Wesche (2003); Holtmeier (2009)
Mount Kenya	00°08'N	5199	3400	Downward	Anthropogenic pressure: fire	Bussmann (2006); Rucina et al. (2009)
Mount Kilimanjaro	03°04'S	5895	3800	Downward	Drought pressure: fire	Hemp (2005); Körner (2012)
Rwenzori Mountains	00°27'N	5109	3900	?	Preserved from anthropogenic pressure	Wesche et al. (2000); Bussmann (2006)
Virunga Mountains[b]	01°14'S	4507	3800 3600	?	Mount Muhabura: Rainfall limited?	Bussmann (2006)

[a] Average treeline elevation

[b] The Virunga Mountains: Mount Karisimbi and Mount Muhabura

2.4.1 Shoulders of the Ethiopian Rift Valley

The Simen Mountains (4540 m) are situated in the northern highlands of Ethiopia and are protected under national legislation since 1969. The Simen Mountains have a unimodal precipitation regime, which is relatively dry compared to the bimodal precipitation regime of the more southern tropical African mountains (Hurni and Stähli, 1982). The treeline formed by *Erica arborea* lies at an average altitude of 3715 m (Hurni and Stähli, 1982). Shifting of this treeline has been observed by repeat photography at Nebir Mekemacha, which shows an increase of the treeline of approximately 120 m from 4000 to 4120 m between 1967 and 1997 (Figure 2.4) (Nievergelt et al., 1998; Wesche et al., 2000). There are two possible explanations for this treeline shift: recent climate change and reduced human and livestock pressure. Evidence against the climatic change hypothesis is given by individual *Erica* trees high above the treeline already in 1968 (Nievergelt et al., 1998). Another possible explanation is the reduced impact of cattle grazing, woodcutting and burning since the National Park was installed (Wesche et al., 2000).

The treeline in the Bale Mountains (4400 m) in southern Ethiopia is formed by *Erica trimera*, which is the dominant species from 3400 up to 4000 m (Figure 2.4). Outliers of individual *Erica* species are even observed up to 4200 m (Miehe and Miehe, 1994). These individuals have a mat-like structure as a result of strong eastern winds (Holtmeier, 2009). Although that the Bale Mountains are also protected since 1969, the upper treeline of the Bale Mountains is lowered by recurrent fires at many places, to maintain or extend the grazing area (Wesche et al., 2000). As a result, mosaics of forests scrubs and afro-alpine grasslands prevail at the treeline in the Bale highlands (Bussmann, 2006).

In both mountain ranges is the treeline located at 4000 m, ca. 400-500 m below the highest summit (Figure 2.4). There is thus a potential impact of the summit syndrome described by Körner (2012). But, observations of recent treeline increase in the Simen Mountains give evidence against the influence of the summit effect at the current treeline elevation.

2.4.2 West Africa

The climate of Mount Cameroon (4095 m) is extremely moist with up to 10 000 mm annual rainfall at lower elevations and 2000 mm at the summit (Bussmann, 2006). Although the western slopes receive more rainfall, this is not reflected in the vegetation profile. The ericaceous specie *Erica mannii*, *Agauria salicifolia* and *Myrica arborea* form the patchy high altitude treeline ecotone (Bussmann, 2006). The abrupt treeline at 3500 m (Figure 2.4) is controlled by periodic volcanic activity, which influences the tree limit directly by destroying existing forest through lava flows and fire and indirectly by unequal deposition of fertile volcanic ashes (Proctor et al., 2007). As a result, the treeline is depressed below its climatic limit (Bussmann, 2006). In addition, there is also a high anthropo-zoogenic pressure through woodcutting, fire and livestock browsing, since the population density is almost twice the average of that in sub-Saharan Africa (Burgess et al., 2007).

2.4.3 Mountain ranges along the Eastern Rift Valley

The *Erica excelsa* treeline at Mount Elgon (4321 m) lies on average at 3300 m and rises up to 3450 m in the humid valleys (Holtmeier, 2009; Wesche, 2003). Despite the negative effects of waterlogging and cold air accumulation, trees grow better in the valleys due to protection from frequent fires. The highest stands in the valleys even occur at 3950 m (Hamilton and Perrot, 1981; Wesche, 2003). The vegetation is, on average every 7-10 year, exposed to high-altitude droughts and thus severe desiccation stress. The impact of drought stress is striking, with up to 50% of the leaves dying, but the plant phenology is little affected (Wesche, 2003). However, the striking consequence of these drought conditions is fire. More than half of the *Erica* and afro-alpine vegetation was burned during the extremely dry conditions of 1997 (Wesche et al., 2000). Extensive burning caused large scale replacement of woody vegetation by grasslands, which recover much faster. As a result of fire and anthropogenic impact by pastoralists the present treeline is depressed below the climatic tree limit (Figure 2.4) (Hamilton and Perrot, 1981; Wesche, 2003).

On Mount Kenya (5199 m), the current boundary between the lower alpine zone and upper *Erica* forest is situated at ca. 3400 m (Figure 2.4) (Bussmann, 2006). The poorly developed Ericaceous forest belt is formed by remnant stands of *Erica excelsa*, *Erica trimera* and *Erica arborea* (Bussmann, 2006). The warmer moister climate of the Holocene enabled the treeline to rise in comparison to LGM levels (Rucina et al., 2009). However, the position of the treeline is currently under high anthropogenic pressure, which is marked by increased fire frequency. This has locally resulted in a transition to open vegetation (Bussmann, 2006; Rucina et al., 2009). The presence of the plant species *Asteraceae Stoebe kilimandscharica* and *Protea kilimascharicaoften* at the treeline, indicate this regular disturbance by high altitude fires. As a result of this disturbances the boundary between the ericaceous belt and the afro-alpine grasses is formed by a patchy mosaic rather than a clear altitudinal boundary (Bussmann, 2006).

The ericaceous belt of Mount Kilimanjaro (5895 m) is formed by *Erica excelsa* forest prevailing above 3000 m, with remnants of *Erica trimera* growing above 3700 m (Hemp, 2009). The treeline is situated at ca. 3800 m, which is below its natural limit (Figure 2.4) (Hemp, 2005; Körner, 2012). In 1976 the treeline reached the 4100 m elevation limit (Hemp, 2009). The cause of the treeline lowering with several hundred meters since 1976 is a drier climate, which caused an increased frequency and intensity of fires on the slopes of the Kilimanjaro (Hemp, 2005). Precipitation has decreased over 30% in the recent years, in particular over the last three decades. More frequent and intensive fires have not only lowered the treeline position, but even caused a deforestation of one third of the Kilimanjaro forest in the last 70 years (Hemp, 2005).

2.4.4 Albertine Western Rift and Congo Nile Crestline

Because of the political instability in this region, scientific studies about treeline dynamics are lacking. The research presented therefore only gives an overview about the current vegetation zonation.

The Rwenzori Mountains (5109 m) are well preserved from anthropogenic influences. There are fires, but these are comparatively small (Wesche et al., 2000). This makes the Rwenzori Mountains one of the most intact Ericaceous vegetation belts of the African tropical highlands (Wesche et al., 2000). The *Erica* forest dominated by *Erica arborea* follows immediately after the bamboo belt (at 3000 m) and marks the treeline at 3900 m

(Figure 2.4) (Bussmann, 2006; Livingstone, 1967). Although the eastern slopes are drier, this is not reflected in the vegetation profile (Bussmann, 2006).

The Virunga Mountains (4507 m) are formed by eight adjacent volcanoes. On the highest peak of Mount Karisimbi the treeline is situated at by average 3800 m. On the drier Mount Muhabura (4127 m) trees are only growing up to 3600 m (Figure 2.4). In the Virunga volcanoes the treeline is formed by *Erica arborea* forest, growing above the *Hagenia abyssinica* and *Hypericum revolutum* forest (Bussmann, 2006).

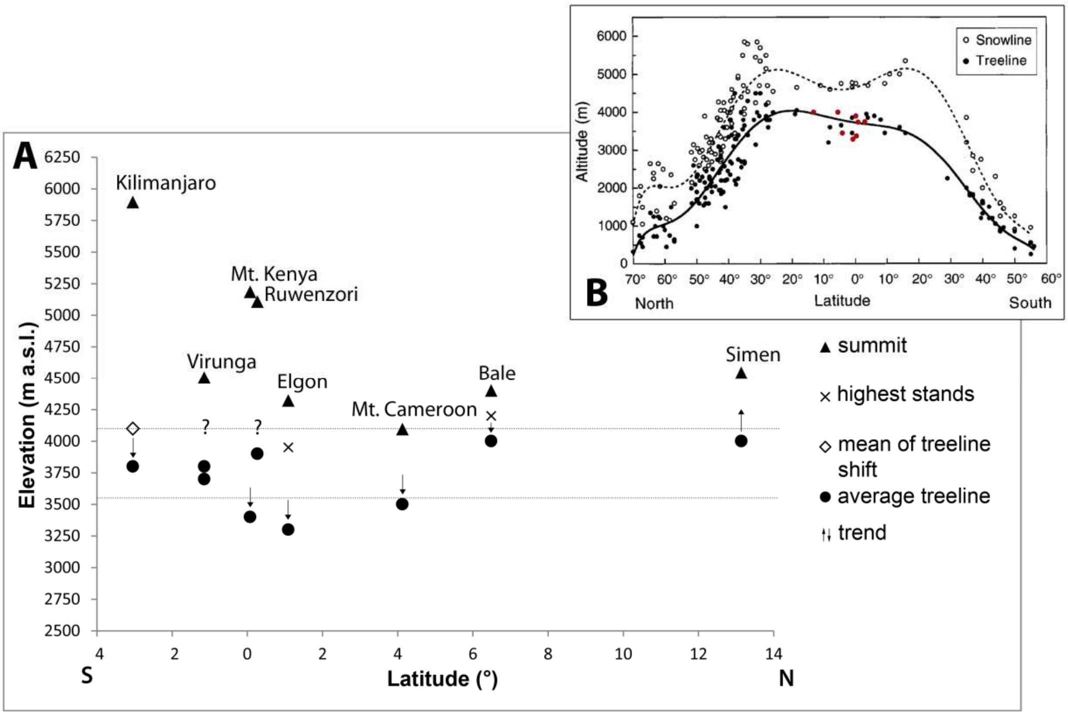


Figure 2.4 Synthesis of treeline dynamics in the tropical African highlands (see Table 2.2 for references). (a) tree line dynamics in the African tropical highlands, arrows indicate the treeline trend. The zone between the dashed lines refers to the upper treeline limit zone described by Hedberg (1951);(b) Körner (1998) adjusted with tree line elevations from the tropical African highlands in red.

2.5 Discussion and conclusion

The discussion is structured according to the two main questions of this paper: (i) understanding the driving factors determining treeline elevation limits and (ii) identifying treeline dynamics in the African tropical highlands.

(i) What are the driving factors determining the treeline elevation in the African tropical highlands?

At present climate change is unequivocal and caused global warming and changing rainfall patterns. These changes have the potential to influence the altitudinal tree growth limit. Unlike in temperate and boreal regions, wind, frost damage and snow accumulation are less important in controlling the treeline position. Treeline species in the tropical highlands must be particularly adapted to high diurnal temperature variation. A temperature increase of 3.3°C by 2100 would correspond with an increase of the tropical African treeline by 550 m, using the vertical temperature lapse rate of East Africa from Peyron et al. (2000) (only taking temperature in account). But, past increases in population pressure in the tropical highlands have depressed the treeline elevation below its climatic limit. Anthropo-zoogenic influences disturb the treeline, mainly by man-made fire to clear the forest for grazing land. The impact of these fires is locally intensified as a result of long term drought, which decreases the resilience of the environment to fire disturbances. Beside this is volcanic activity also a locally important constraint of high altitude tree growth.

(ii) Are treelines in the African tropical highlands subjected to change?

Hedberg (1951) presented a general classification of the vegetation belts of the Eastern African Mountains. He recognized three belts on each mountain: the alpine, the ericaceous and the montane forest belts. The treeline is situated in between the alpine and ericaceous belt with an elevation limit between 3550 and 4100 m (Hedberg, 1951). This 4100 m-limit corresponds with the treeline in the Simen Mountains at present. The Simen Mountains are the only mountain range in this study of which the treeline rose locally. This indicates that here, the tropical treeline lies below its potential climatic limit (Bader, 2007; Kessler, 1995; Miehe and Miehe, 1994). A tentative explanation is that the Simen Mountains are located most northern and thus closer to the subtropics and as a result receive less rainfall and cloudiness, which can cause the treeline to rise higher (Körner, 2012). But this explanation is too simplistic, because locally decreasing human impact after national park establishment should also be taken into account.

However, the general trend is that treelines were moved down due to high anthropo-zoogenic pressure and especially fire (Bader, 2007; Ellenberg, 1996; Hemp and Beck, 2001; Kessler, 1995; Miehe and Miehe, 1994; Wesche et al., 2000). This is the case for most of the mountain ranges studied. In the Bale Mountains, Mount Elgon, Mount Cameroon and Mount Kenya, the treeline is lowered due to high anthropogenic pressure. In addition, on Mount Cameroon volcanic activities have also had a negative effect on the treeline elevation. Disturbance by human and livestock is controlling the treeline elevation at elevations below their natural climatic limit in many African tropical mountain ranges. In the Rwenzori and Virunga Mountains the human pressure is lower because of the politic instability in this region. As a result is the treeline elevation potentially more stable. Yet, little is known about potential vegetation shift in this region. When neglecting human interference, treelines in the tropical African highlands might rise to higher elevations. This is witnessed in the Simen Mountains, although decreasing pasture and wood cutting also played a major role here. A hypothetical upper treeline limit at 4100 m is suggested by Hedberg (1951). The 4100 m-limit as suggested by Hedberg (1951) used to be also corresponding with the limit at the Kilimanjaro in 1976. But due to climatic drier conditions in combination with growing anthropogenic pressure is the treeline of the Kilimanjaro also lowered. The effect of decreasing rainfall conditions is thus opposite between the Simen Mountains and the Kilimanjaro.

Overall, treelines in the African tropics are strongly disturbed by human and livestock pressure, which makes it not possible to use them as a proxy of climate change in the tropics. The general trend of a depressed treeline below the climatic limit in the tropical African highlands favours the hypothesis that treelines are still moving upwards from lower positions due to a slow response time to climate change (Holtmeier, 1994; Wardle and Coleman, 1992). Because shifts in species distributions may lag behind climate changes (Dullinger et al., 2012). But evidence against this hypothesis is given by past higher treeline elevations and by evidence of a rising treeline in the Simen Mountains.

(iii) Outline for future work

Overall, more treeline research in the African tropical highlands is vital to improve the scientific understanding of the response of high altitude tropical treelines to environmental changes. In the global treeline research of Harsch et al. (2009), continental Africa is a blank spot on the map. The IPCC has recognized this need to understand the ecosystem dynamics and climate variability in Africa. Climate change may have important effects on the functioning of the ecosystems of the African tropical highland. A better understanding of this can help to make realistic predictions, which are important as an input to land management scenarios.

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Chapter 3 Geomorphology and paleoclimatic significance

This chapter is based on:

Hendrickx, H., Jacob, M., Frankl, A., Nyssen, J. (2015). Glacial and periglacial geomorphology and its paleoclimatological significance in three North Ethiopian Mountains, including a detailed Geomorphological map. Geomorphology, accepted for publication.

Abstract

Geomorphological investigations and detailed mapping of past and present (peri)glacial landforms is required in order to understand the impact of climatic anomalies. The Ethiopian Highlands show a great variety in past and contemporary climate, and therefore, in the occurrence of glacial and periglacial landforms. However, only a few mountain areas have been studied, and detailed geomorphological understanding is lacking. In order to allow a fine reconstruction of the impact of the past glacial cycle on the geomorphology, vegetation complexes, and temperature anomalies, a detailed geomorphological map of three mountain areas (Mt. Ferrah Amba, 12°51'N 39°29'E; Mt. Lib Amba, 12°04'N 39°22'; and Mt. Abuna Yosef, 12°08'N 39°11'E) was produced. In all three study areas, inactive solifluction lobes, presumably from the Last Glacial Maximum (LGM), were found. In the highest study area of Abuna Yosef, three sites were discovered bearing morainic material from small late Pleistocene glaciers. These marginal glaciers occurred below the modelled snowline and existed because of local topo-climatic conditions. Evidence of such Pleistocene avalanche-fed glaciers in Ethiopia (and Africa) has not been produced earlier. Current frost action is limited to frost cracks and small-scale patterned ground phenomena. The depression of the altitudinal belts of periglacial and glacial processes during the last cold period was assessed through periglacial and glacial landform mapping and comparisons with data from other mountain areas taking latitude into account. The depression of glacial and periglacial belts of approximately 600 m implies a temperature drop around 6°C in the last cold period. This cooling is in line with temperature depressions elsewhere in East Africa during the LGM. This study serves as a case study for all the intermediate mountains (3500–4200 m) of the North Ethiopian highlands.

Keywords**:** glacial and periglacial geomorphology; avalanche-fed glacier; Quaternary environment; paleoclimate

3.1 Introduction

During the Pleistocene, the Earth was exposed to severe climate fluctuations (Kaser and Osmaston, 2002). This resulted in different large ice extents; whereas, especially the last cold period (Last Glacial Maximum (LGM) from 26.5 to 19.0 ka; (Clark et al., 2009), reshaped the affected landscape. The LGM cooling did not only affect the mid- and high-latitudes, but also the tropics (Mark and Osmaston, 2008; Seltzer, 2000). With lots of research on the LGM in the higher latitudes, less is known about the LGM in the tropics (Benn et al., 2005). The past ice equilibrium line (Equilibrium Line Altitude, ELA) is a good tool to allow reconstruction of past climates (Hastenrath, 2009). One of the methods to establish the past ELA is to analyse past landforms caused by cold environment geomorphological processes, such as morainic features (Benn et al., 2005). Geomorphological research with focus on periglacial and glacial landforms allows having a better insight in the spatial variability of present and past climates.

Although recent glaciations around the tropics are limited to small, mostly vanishing glaciers on high peaks, landforms of past glaciations are more prominent and have been described at the Drakenberg of South Africa, the Atlas Mountains, the high volcanic plateaus and the equatorial high mountains of East Africa (Kaser and Osmaston, 2002). In the Ethiopian Highlands, at least three mountain regions bear evidence of past glaciations (Mark and Osmaston, 2008). Below historical glaciers, presumably LGM age, evidence of intense periglacial activity has been observed (Osmaston and Harrison, 2005). Observations from the Simen, Arsi, and Bale mountains and Mt. Guna were summarized by Hendrickx et al. (2015). The Simen Mountains are located around 150 km northwest of the study area. There, the Pleistocene ELA depends on slope aspect and is reconstructed at 4100–4400 m (above sea level a.s.l.) (Hurni, 1981). Furthermore, observations suggested that the temperature dropped by 7°C during the LGM (Hurni and Stähli, 1982). The LGM temperature drop in East Africa was, in general, around 5–6°C (Osmaston and Harrison, 2005; Osmaston, 2004). At present geomorphological processes in the Ethiopian Highlands are mainly driven by gravity, water, and human activities (Nyssen et al., 2004).

Although many geomorphological investigations were done in Ethiopia (e.g., Hastenrath, 1974; Williams et al., 1978; Hurni, 1989; Billi and Dramis, 2003; Nyssen et al., 2004; Moeyersons et al., 2008), few led to detailed and holistic geomorphological maps (e.g., Hurni, 1981; Coltorti et al., 2009; Poppe et al., 2013). Therefore, studying and accurately mapping these landforms is important in order to reconstruct past climate conditions in the past.

The aims of this paper are (i) to present a detailed geomorphological map with focus on glacial and periglacial landforms of three tropical mountains in the North Ethiopian highlands, using remote sensing and an intensive field campaign; (ii) to confirm the genesis of the mapped landforms by sedimentological analyses regarding clast size, orientation, and matrix textures and (iii) to reconstruct the paleoclimate during the LGM in the study area. This study serves as a case study for the middle range mountains (3500–4000 m a.s.l.) in the North Ethiopian highlands, where glacial and periglacial research is limited.

3.1.1 Study area

The Ethiopian Highlands are composed of high volcanic plateaus with summits ranging above 4000 m. The study area consists of three mountain areas above 3500 m (Mt. Ferrah Amba, 12°51’N 39°29’E; Mt. Lib Amba, 12°04’N 39°22’; and Mt. Abuna Yosef, 12°08’N 39°11’E) where no earlier research was done on glacial and periglacial landforms (Figure 3.1), although the existence of an avalanche-fed glacier had been suspected from an oblique aerial photograph of Mt. Abuna Yosef (Hendrickx et al., 2015).

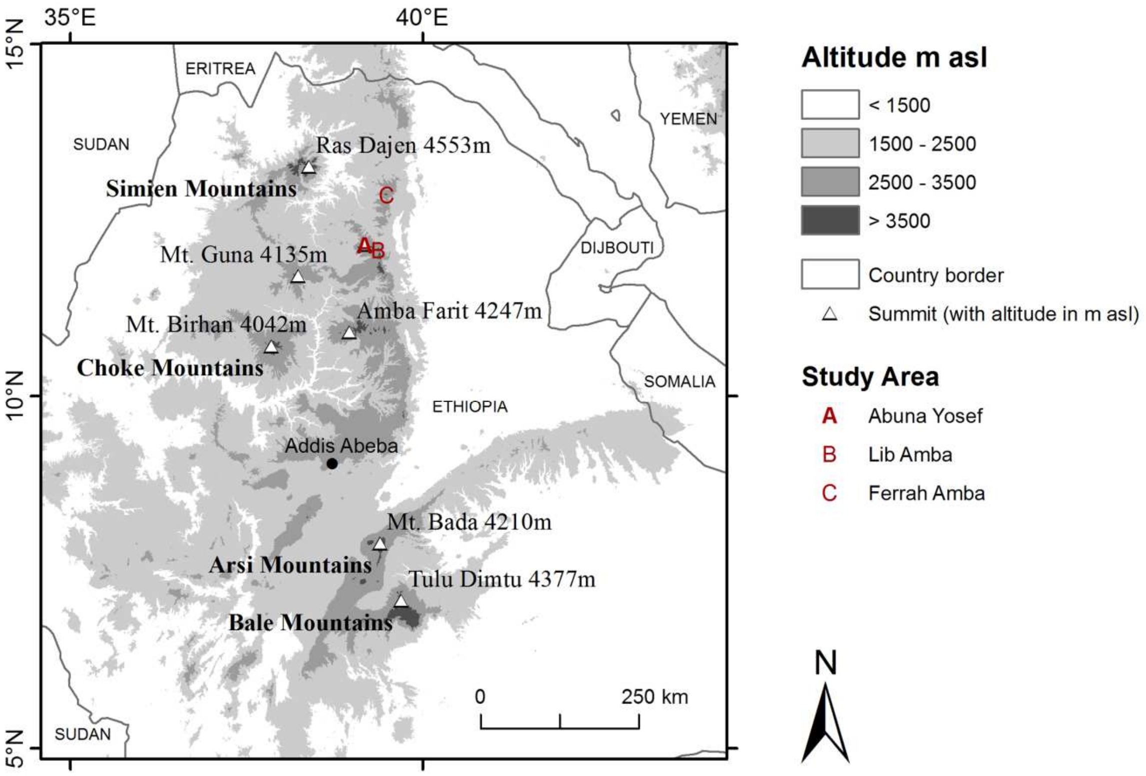

Figure 3.1 Map of the Ethiopian Highlands.

The study area is composed of successive lava flows, which formed in near-horizontal, Tertiary basalt layers, known as the Ethiopian trap basalt series (Umer et al., 2004). These stratified basalt series can be more than 2000 m thick and cover the formations of the Mesozoic sandstone and limestone, and Palaeozoic and Precambriam basement rocks

(Kazim, 1975, 1973). Inactive volcanic plugs and structural relief characterize the study area, forming steep escarpments. With elevations reaching 4500 m, the Ethiopian plateau was high enough to be partially glaciated during the LGM (Mark and Osmaston, 2008).

Local topography has a strong control on cloudiness and precipitation in the East African mountains. Precipitation in the Ethiopian mountains varies with latitudes, altitude and aspect (Rosqvist, 1990; Nyssen et al., 2004; 2005; Mark and Osmaston, 2008). Areas closer to the equator will have a longer wet season that tends to be bimodal, caused by the annual movement of the Intertropical Convergence Zone (O'Hare et al., 2005). The rainfall distribution in the Simen Mountains shows two maxima around 1800 and 3600 m (Messerli and Winiger, 1992), but detailed rainfall information about the study area is still lacking. Glacier limits reached lower on western slopes in East Africa (On the Kilimanjaro, Mt. Kenia, and Ruwenzori) because of the maximum cloudiness and precipitation in the afternoon, reducing the solar radiation on west-oriented slopes (Hastenrath, 2009, 1974; Rosqvist, 1990). All high mountains in East Africa are situated within 15° from the equator, but solar radiation still differs between north- and southward-facing slopes (Rosqvist, 1990). Thus, local topography can control solar radiation and precipitation (Seltzer, 2000). The current 0°C isotherm in East Africa lies around 4750 m, but ELAs of current glaciated areas are often located higher, in the isothermal range of -7 to -10°C (5400–5800 m) for the Kilimanjaro and 0° to -2°C for Ruwenzori (4600 m) (Rosqvist, 1990). According to the temperature gradient, contemporary permanent snow and glaciation could appear above 4800 m, but this exceeds the highest peaks of Ethiopia (Hurni, 1989). Structured interviews with key informants revealed that snowfall irregularly occurs above 3500 m, mostly during the dry season and in August. In general, snow cover rapidly melts away by noon; but on high, overshadowed places it can stay for a couple of days.

3.2 Material and methods

3.2.1 Data collection and mapping of geomorphological imprint of the Pleistocene environment

Geomorphological mapping is a powerful scientific tool used to understand landscape configuration and development (Gustavsson et al., 2006). It is especially useful to reconstruct climatic changes in a former glacial and periglacial environment (Pavlopoulos et al., 2009). In order to map the variety of geomorphological processes active during the Pleistocene and the current climate, an integrated analysis was carried out based on a digital elevation model (DEM), interpretation of stereoscopic aerial photographs

(Table 3.1), and intensive field investigations (July–September 2013) (Frankl et al., 2010; Annys et al., 2014). Global Navigation Satellite System (GNSS) data was collected from small-scale landforms and from 13 profiles (Figure 3.2). In total, around 1400 points of interest were recorded using a Garmin eTrex H handheld global positioning system (GNSS, < 10 m RMSE) (Figure 3.2). The geographic datum used is the WGS 84, projected in UTM 37N.

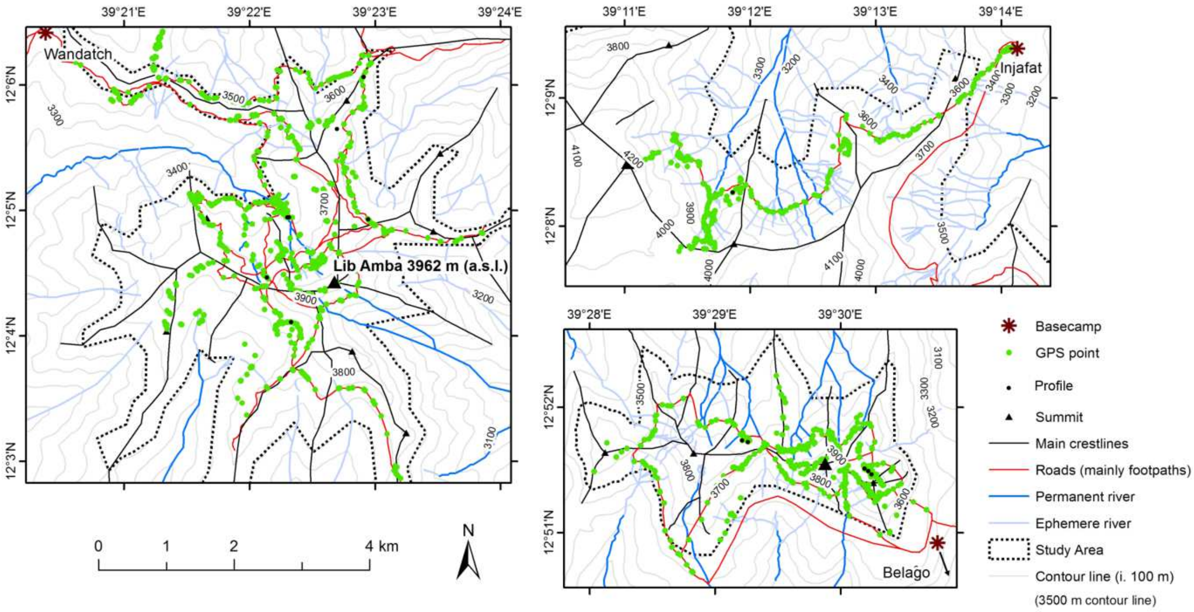

Figure 3.2 Distribution of points of interest taken in the field with a hand-hold GNSS.

Observations were made on geology, morphography/morphometry, hydrology, and anthropogenic and vegetation characteristics. General morphological structures were observed during the fieldwork, such as inactive volcanic plugs, structural relief, basaltic dykes, alluvial fans, debris and rockfall of varying size, landslides, channel morphology, and gullies. Slope gradients were measured with a clinometer.

The fieldwork especially focussed on glacial and periglacial landforms. Features that were recognized during the field survey are scree slopes, solifluction lobes, soil creep, frost cracks, polygon patterns, and morainic features from avalanche-fed glaciers. These glaciers mostly occur below the climatic ELA because they are nourished by avalanches and windblown snow (Hughes, 2007). This suggests the existence of local topographic conditions favouring the permanence of snow, today and in the past. To support this statement, the avalanche ratio was calculated for each avalanche-fed glacier site. This is the ratio between the total area contributing to avalanches (slope > 30%, *V*) leading directly onto the glacier area (*A*) (Carturan et al., 2013; Hughes, 2007).

Table 3.1 Remotely sensed information and maps used in this study

Type	Date	Number	Resolution	Source
Satellite imagery	2012	N.D.	2.5 m	Bing Maps
	2006	N.D.	2.5 m	Google Earth
Topographic map	1999	Lalibela – ETH 4 1239 C3 Muja – ETH 4 1239 C4	1:50000	Ethiopian Mapping Agency
	1996	Maychew – ETH 4 1239 B1 Bora – ETH 4 1239 A2	1:50000	Ethiopian Mapping Agency
ASTER digital elevation model	2011	43-10; 43-11; 44-10; 44-11; 44-12; 45-10; 45-11; 45-12; 46-11	30 m grid	NASA Earth Data
Aerial photographs	February 1980	ET2/F11/262 1795-96 ET2/S11/27 03556-57 ETH2/S11/29 0388-89-90 ETH2/S11/30 0435-36-37 ET2/F11/311 2222-23	± 1:50000	Owned by Ethiopian Mapping Agency, performed by SWEDSURVEY

Based on the approach described here-above, a highly detailed terrain-fitting legend was developed (Appendix A). The legend type is based on maps by Hurni (1981) in the Simen Mountains, on general approaches for mapping (peri)glacial environments (Pavlopoulos et al., 2009) and some specific case studies (De Graaf et al., 1987; Frankl et al., 2010; Annys et al., 2014), and is constructed according to the AGRG (Applied Geomatic Research Group) mapping system, first developed by De Graaf et al. (1987). The integration into a Geographical Information System (ArcGIS 10.1 ESRI) was based on Gustavsson et al. (2006), whereas the upper layers consist out of point data, followed by line and polygon shapefiles. The results are presented on a geomorphological map at a 1:20 000 scale (Appendix A).

A one-way ANOVA and a Kruskal-Wallis test were used to detect whether the occurrence of periglacial lobes is more frequent on north slopes.

3.2.2 Field and laboratory sedimentological analysis

In total, 13 profile analyses were conducted. In Lib Amba, seven profile analyses were made where road cuts already exposed interesting soil profiles. The lower limit of buried periglacial rubble was also determined by considering exposed soil profiles, according to the methodology of Hurni (1989). Periglacial rubble was recognized as angular clasts that are oriented parallel to the slope angle. When embedded in a yellow-brown matrix of loamy silt, the deposit is defined as a solifluction horizon. In Ferrah Amba, where there are no road cuts, five profile locations were selected when a clear landform was present. In Abuna Yosef, a profile pit in a moraine was excavated.

To define the genesis of the landforms, the degree of sorting, orientation, clast shape and size, and other sediment characteristics were investigated in each profile. Rock fragment density in the profile was also recorded by counting the amount of rock fragments along a line of 2-3 m. Per, profile, 50 elongated clasts from the matrix were analyzed. The orientation was measured with a compass, and clast size and shape properties were measured on the basis of *a*-, *b*-, and *c*-axial lengths, using a caliper with 1 mm accuracy (Millar, 2005). This clast-derived information informs about the genesis of the landform and the environment in which the sediment had moved. Because of the thick soil cover and abundant vegetation on the lobes, the landforms are considered to be inactive and relict features. Even when undercut by roads, the lobes were not reactivated.

Matrix samples were collected for texture analyses through sieving. In total, six samples were collected in the field. In Lib Amba, five samples were collected from locations where a profile analysis was also done. One sample was taken from a regular Andosol soil as comparison. In Ferrah Amba, a sample was taken from a solifluction horizon. In order to avoid stones in the sample, a sieve with mesh opening of 16 mm was used to prepare the samples in the field.

Because the matrix in the Simen Mountains found by Hurni (1989) mostly contained clayey silt, silt, and sand, a standardized nested column of sieves with different mesh openings for these particular sediments were used. The smaller fraction (< 0.063 mm) of each sample was analysed with the sedigraph (http://www.micromeritics.com, 10 May 2014). Together with the clast analysis, this gives more insight in landform genesis.

3.2.3 Reconstruction of paleoclimate by using geomorphological information

The ELA is often used for paleoclimatic reconstructions and can be calculated from position of morainic material (Nesje and Dahl, 2000). Because the periglacial belt is parallel to the ELA (Hurni, 1981), the altitudinal differences between the past lower limit of the periglacial belt and the present lower limits of periglacial processes can be used to reconstruct the paleo ELA and therefore the paleoclimate. According to Hurni (1981), a depression of 100 m corresponds with a 1°C cooling in the Simen Mountains. This corresponds with the dry adiabatic lapse rate (O'Hare et al., 2005), which is considered a representative lapse rate for the dry conditions during the last cold period. By conducting a detailed mapping of past periglacial belts and interpolation from current periglacial belts, the altitudinal depression was assessed.

3.3 Results

3.3.1 Glacial and periglacial features

The geomorphological maps include a detailed geomorphological representation of the three mountainous areas, Abuna Yosef, Lib Amba, and Ferrah Amba, including glacial and periglacial landforms (Table 3.2) and general geomorphology, such as structural escarpements, dykes, crest lines and valleys (Figure 3.3).

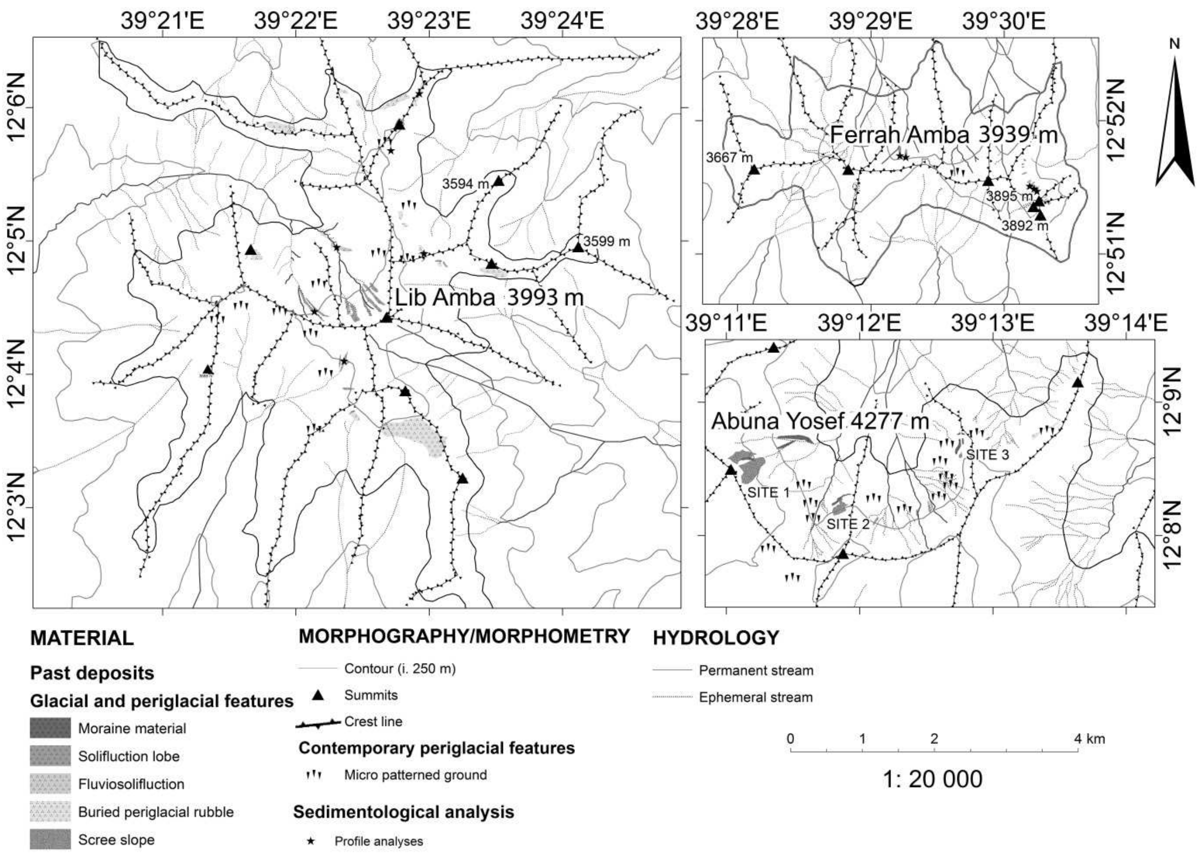

Figure 3.3 Geomorphlogical sketch of the studied North Ethiopian mountains, based on the detailed geomorphological map (Appendix A).

Table 3.2 Glacial and periglacial features observed

Interpretation of the feature	Obs.[a]	Width (m) Mean ± std	Length (m) Mean ± std	Aspect	Altitudinal range (m)	Slope (%)	SA[b]	Fig.
Moraine	8	36.9 (±17.0)	219.6 (±148.3)	NW-NE	3650-3900	Level	A	3.3
Solifluction lobe	41	26.2 (±13.9)	157.1 (±127.9)	NW-NE	3650-3900	10 – 20	A,B,C	3.6A
Fluvio-solifluction	9	26.3 (±14.9)	75.6 (±56.6)	NW-NE	3500-3750	15 – 25	A, B	
Buried periglacial rubble	16	82.4 (±59.1)	245.2 (±201.1)	No data	Down to 3500	No data	A, B	3.5A
Scree slope	5	56 (±57.4)	91 (±81.7)	NE-N	3700-3900	> 20	A, B	3.6B
Frost cracks	59	No data	No data	SW-NE	3600-4100	Level	A, B	3.7A

[a]Field observations; [b]Study areas: (A) Abuna Yosef, (B) Lib Amba, (C) Ferrah Amba

Moraines of avalanche fed glaciers on the Abuna Yosef

Morainic features were only found in Abuna Yosef (Table 3.3). On three different locations in the area around the highest peak, avalanche fed glaciers existed during the past cold conditions (Figure 3.4). The first location is the slope underneath the Abuna Yosef peak itself (12°10’32.27”N, 39°10’59.13”E), which consists out of a very impressive inactive plug, rising very high and steep above the surrounding landscape (Figure 3.4, site 1). The plug casts a wide topographic shadow in the close surroundings of the peak. This favoured the climatic condition for the occurrence of an avalanche-fed glacier (AFG). There is even an undercut area where the volcanic plug is overhanging. Big boulders caused by rock fall characterize the north slope of the plug. Possible evidence of a glacier could be deeply buried by this active rock fall. At the lower end of the rock fall slope, morainic features were present. Slope debris is pushed together to form several ridges. The rock fall underneath the Abuna Yosef forms a broad valley cutting through the structural landforms on a scale that is unique in the study area (Figure 3.4, site 1).

Table 3.3 Avalanche fed glaciers sites on the Abuna Yosef

Site	**Lat. (°N)**	**Long. (°E)**	**A (ha)**[1]	**V (h)**[2]	**V/A**[3]	**Alt. range (m a.s.l.)**	**Observations**
S1	12°08’30”	39°11’10”	23	20	0.87	3533 – 4208	Moraine material highly disturbed by recent rock fall.
S2	12°08’17”	39°11’10”	6	18	3.03	3669 – 3757	Clear moraine ridges and moist depressions. Profile pit analysis.
S3	12°08’37”	39°12’45”	4	7	1.75	3641 – 3700	Clear moraine ridges and moist depressions.

[1]A = Extent glacier site (ha); [2]V = Uphill extent (ha); [3]V/A = Avalanche ratio

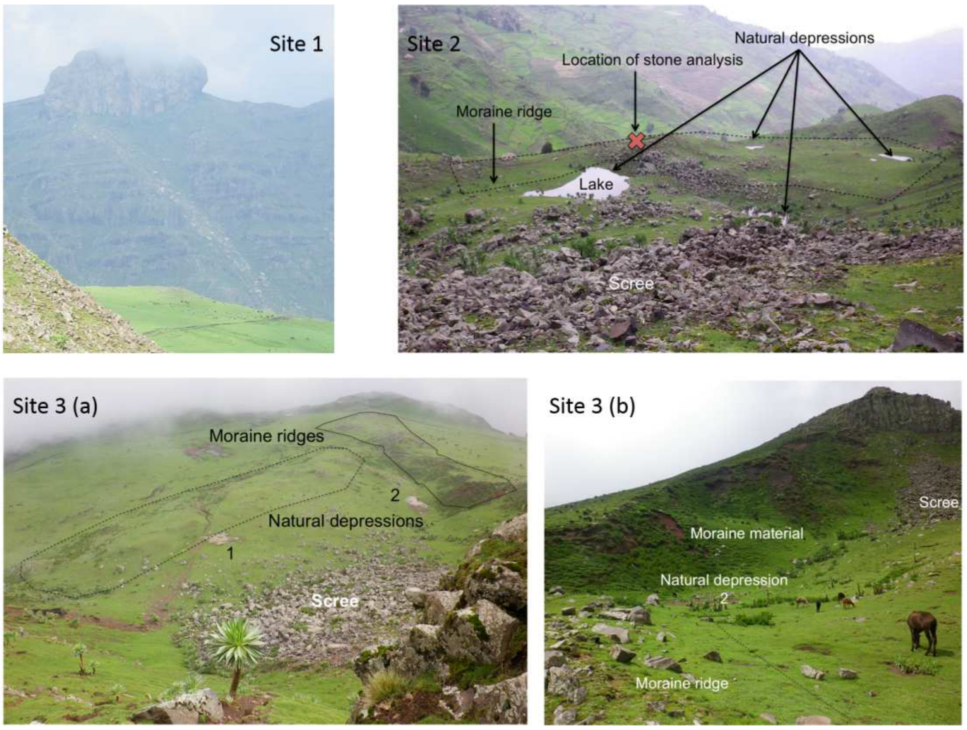

Figure 3.4 Three avalanche-fed glacier sites in the Abuna Yosef massif, indicating morainic features, screes and natural depressions.

Two other AFG were found in the area and are more pronounced and less disturbed by active rock fall. In both of the AFG sites, several small ponds and natural humid depressions were present, closed off at the lower side by a ridge of blocky material. The steep slope that casts a shadow over this ridged-bordered depression bares an active scree. A profile pit was dug at site 2 to examine the clast characteristics of the morainic material (Figure 3.4, site 2). The very angular clasts were between 10 and 20 cm, characterized by sharp and smooth edges and embedded in a fine matrix of yellow-brown loamy silt.

The drainage area leading directly onto the former glacial extents of the three sites, consists mainly of very steep slopes (> 30%) and structural escarpments (Figure 3.5). Thus, the drainage area is considered to be a potentially avalanche-controlled area and is used to calculate the avalanche ratio (Table 3.3) (Carturan et al., 2013; Hughes, 2007). The avalanche ratio (V/A) for sites 1, 2, and 3 is 0.87, 3.03, and 1.75.

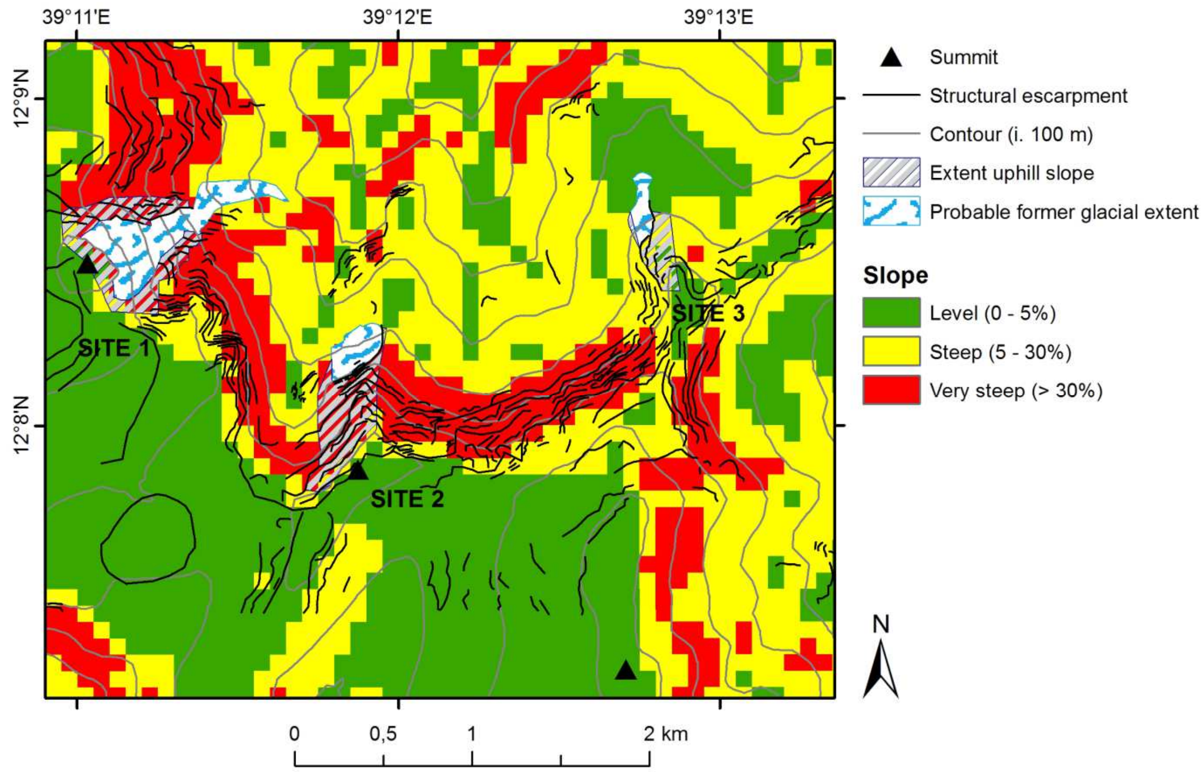

Figure 3.5 Slope map of the three avalanche-fed glacier sites, with the probable former glacial extent and extent uphill slope used for calculation of the avalanche ratio in Table 3.3.

Solifluction lobes, blockfields and angular rubble

In the entire study area, periglacial features are present. The most remarkable of these features are the solifluction lobes (Table 3.2). Where solifluction activity did not make pronounced landforms, periglacial rubble can be observed in road cuts and in profile pits (Figure 3.6). Only in the study area of Lib Amba was the lower limit of the buried periglacial rubble was detected at around 3500 m. Because of the lack of road cuts in Ferrah Amba, no lower limit of periglacial rubble could be detected.

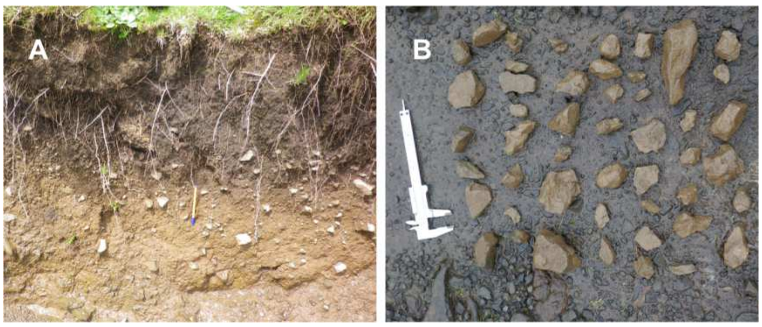

Figure 3.6 (A) Periglacial rubble exposed by a road cut in Lib Amba, and (B) 50 stones, irregularly shaped and angular, from a solifluction lobe.

Fluvial activity may rework periglacial material and move it downslope (Hurni, 1989). These deposits are sandier and contain more rounded clasts. In the study area of Lib Amba, fluviosolifluction material is found down to 3500 m on the north side of its highest peak. No reworked fluviosolifluction material was found in Ferrah Amba.

Although many steep, rocky slopes are present in Ferrah Amba because of structural escarpments, little active scree slopes were observed in the study area. At the northern flank of Lib Amba (3962 m), close to the summit, small scree slopes were detected. In contrast with the two other study areas, steep slopes in the Abuna Yosef often carry big active scree deposits (Figure 3.7B). On the steep slopes around possible AFG sites, large scree slopes were also observed.

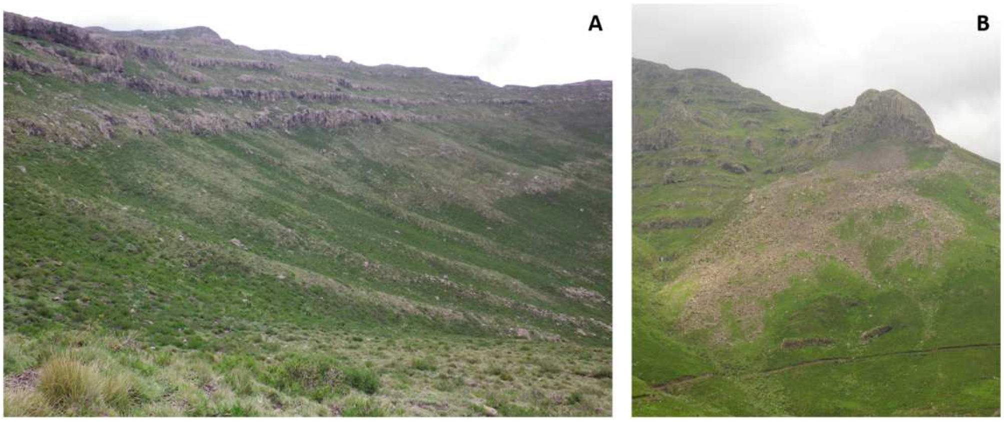

Figure 3.7 Periglacial features observed. (A) Solifluction lobes on a north-oriented slope in Ferrah Amba and (B) large scree slope in Abuna Yosef.

Patterned ground phenomena and frost cracks

Large, patterned ground phenomena and needle ice were not observed in the study area, only micro-patterned ground features of current frost action were found as a result of contraction of the soil (Table 3.2). These frost cracks, sometimes polygon shaped (10 to 20 cm across), are found in Abuna Yosef, Lib Amba, and Ferrah Amba down to 3600 and 3650 m (Figure 3.8). In the Abuna Yosef, more pronounced features were observed near streams, approximately 1 m in diameter.

Patterned ground phenomena were found on high, relatively level areas with only afro-alpine grasses. In moist environments, around streams and natural depressions, more frost phenomena could be observed.

Figure 3.8 Frost cracks (A) and evidence of frost (B, C) in Lib Amba. Where (B) is ice, (C) is upheaval of the soil by needle ice.

3.3.2 Glacial and periglacial features – clast and sedimentological analyses

The main results of the landform analyses consider the correspondence between landform and clast characteristics. Clast dimensions were measured and the Flatness Index (FI; Cailleux, 1945) was calculated (Table 3.4).

Table 3.4 Landform-clast characteristics

Feature	Mean clast dimensions (cm) (n=50) a	b	c	FI	Volumetric stone content (%)	Clast shape[a]	Aspect
Landslide rubble LA1	7.5 (±3.3)	5.2 (±1.9)	3.3 (±1.3)	1.92	52	SR	NW
Fluviosolifluction LA2	6.2 (±3.1)	4.3 (±2.3)	3.7 (±1.4)	1.42	37	SA	NW
Solifluction lobe LA3	5.5 (±1.9)	4.7 (±1.1)	2.1 (±1.0)	2.43	71	A	NW
Fluvio-Solifluction lobe LA4	4.3 (±1.6)	2.7 (±1.0)	1.8 (±0.8)	1.94	47	SA	S
Buried rubble LA5	3.8 (±2.0)	2.4 (±1.1)	1.6 (±0.7)	1.94	40	SA	E
Buried rubble LA6	4.5 (±2.0)	2.9 (±1.4)	1.8 (±0.9)	2.06	51	A	E
Fluvio- solifluction lobe LA7	6.2 (±2.2)	4.2 (±1.7)	2.9 (±1.2)	1.79	84	SA	E
Solifluction lobe FA1	5.0 (±2.0)	3.3 (±1.4)	2.2 (±1.0)	1.89	50	A	NE
Solifluction lobe FA2	5.0 (±2.2)	3.5 (±1.6)	2.3 (±1.0)	1.85	40	A	NE
Solifluction lobe FA3	4.4 (±1.8)	3.1 (±1.3)	1.9 (±1.1)	1.97	43.5	A	NE
Solifluction lobe FA4	4.5 (±1.4)	2.9 (±0.9)	1.7 (±0.7)	2.18	47	A	N
Solifluction lobe FA5	3.8 (±1.4)	2.7 (±1.3)	1.7 (±0.5)	1.91	28	A	N
Moraine AY	10–20	ND	ND	ND	ND	VA	N

[a]SR = subrounded, SA = subangular, A = angular, VA = very angular; ND = No Data

The solifluction lobes consist of angular clasts that are oriented parallel to the slope angle and are often embedded in a yellow-brown matrix of loamy silt. Over 40 solifluction lobes were observed in the entire study area. They occur mostly on northern slopes and reach down to 3650–3670 m (Figure 3.9A).

The solifluction lobes in Ferrah Amba were found on north and north easterly facing slopes (Figure 3.9B), close to each other (Figure 3.7A). The major axis of most of the stones in the profile (60-80%) is parallel to the slope direction. All solifluction lobes had similar distributions of the different clast shapes, with mainly angular and subangular clasts.

The solifluction lobes in Lib Amba were mainly found on the north, northwestern, and western slopes around the highest peak (Figure 3.9A). They consist of mainly angular and subangular stones. The major axis of most of the stones in the profile (60-80%) is parallel to the slope direction.

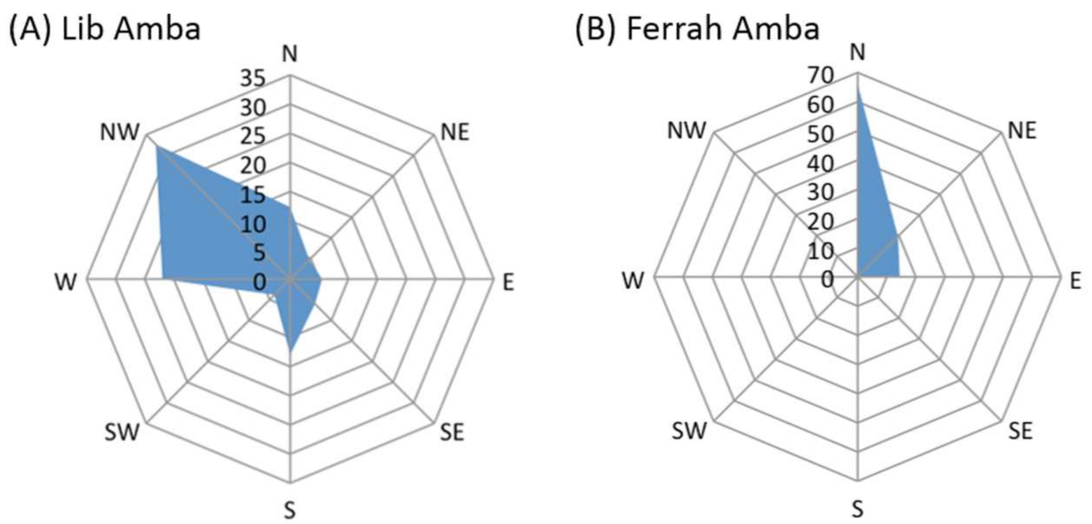

Figure 3.9 Compass card with the percent of area of solifluction lobes for each orientation for the study area of Lib Amba (A) and Ferrah Amba (B).

Other profile analyses were interpreted as landforms with a different genesis. Profile analysis LA1 (Table 3.4) is interpreted as landslide rubble, with more rounded and less elongated clasts. The stones are also less prominent directed in the slope directions. The matrix that embedded the clasts was a dark sandy soil in contrast with the yellow-brown matrix of loamy sand observed in the solifluction profiles. Profile analyses LA2, LA4, and LA7 were interpreted as fluviosolifluction material with more subangular and subrounded stones.

Additional information about landform genesis was derived from the texture analyses of the matrix. The matrix of LA2 is clearly sandier than the matrix of the solifluction lobes (FA5 and LA6), where the finer fractions are more represented (Figure 3.10). The coarser matrix texture is also an indication of water disturbance. The matrix of LA4 is sandier and the landform was probably disturbed by fluvial processes. The andosol soil consists of the finest material and is black, unlike the matrix of (fluvio)solifluction material (Figure 3.10). It originates from weathered volcanic bedrock.

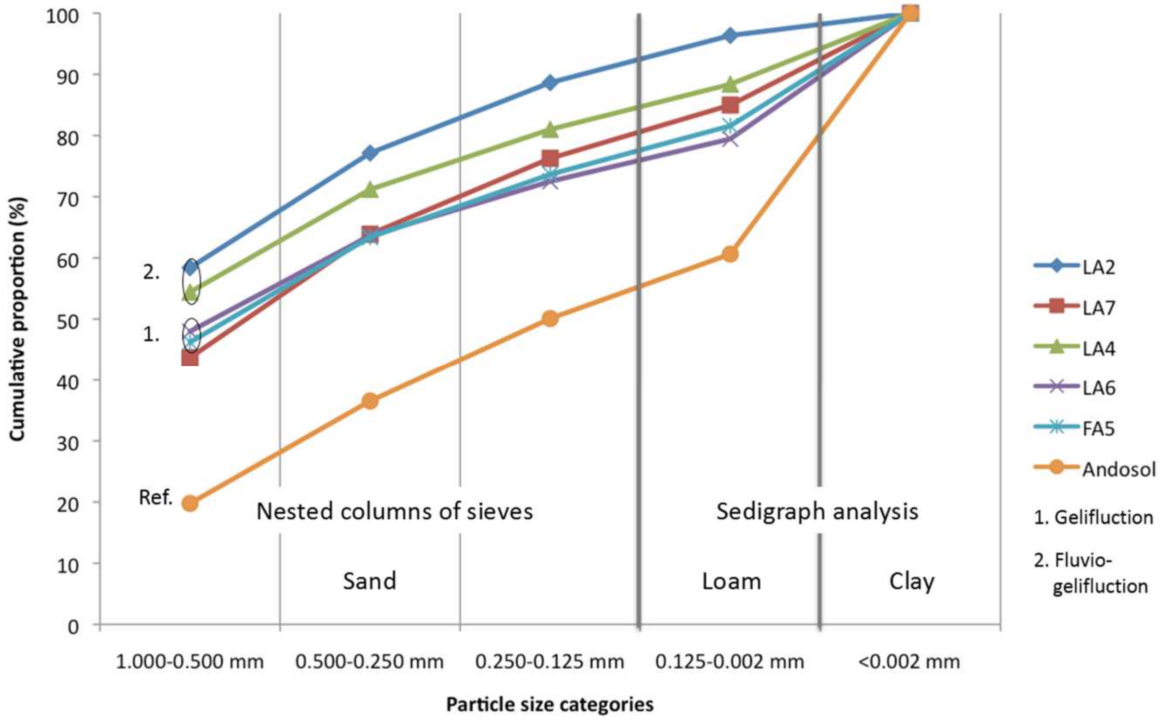

Figure 3.10 Results of laboratory soil texture analysis in a cumulative curve for the different soil classes.

An additional analysis was conducted in the Abuna Yosef. On site 2 of an AFG, a profile pit was dug over the moraine in order to analyse the morphometry of 100 stones not exposed to surface weathering (indicated on Figure 3.4, site 2). The stones are in an order from 10 to 20 cm and very angular with three to four flat surfaces. These angular blocks were interpreted as frost weathered rock because of typical straight, smooth surfaces with sharp edges. No striations of any kind were found on the deposited stones.

3.3.3 Glacial and periglacial features – construction of altitudinal belts

Current and past altitudinal belts were reconstructed from observations in the field (Figure 3.11, Figure 3.12). Only in the study area of Abuna Yosef, a small and very local glacial belt is present. The inactive solifluction lobes found in the field are assumed to date from the LGM, although absolute dates are lacking. Similar observations in the Simen and Bale Mountains also report LGM-aged features (Hurni, 1981; Mohammed and Bonnefille, 1998; Osmaston et al., 2005).

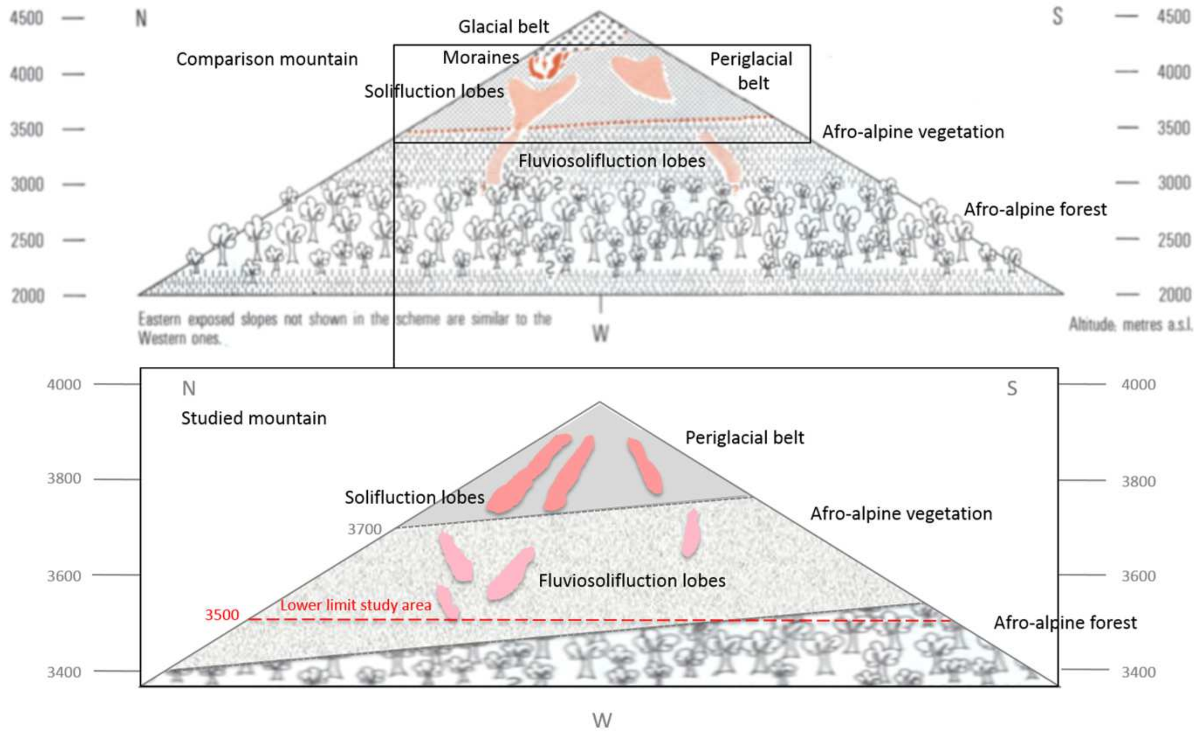

Figure 3.11 Altitudinal belts of the LGM for the study area based on observations in the field in comparison with the altitudinal belts for the Simen Mountains (top figure by Hurni (1981).

The difference between northern and southern slopes is clear (Figure 3.11). Eastern slopes are similar with western slopes. An afro-alpine forest presumably existed underneath the periglacial and the grass belt, but no field observations confirmed this. In general, the altitudinal belts of the LGM for the study area reach higher altitudes than the altitudinal belts observed in the Simen Mountains by Hurni (1981) based on geomorphological evidence (Figure 3.11).

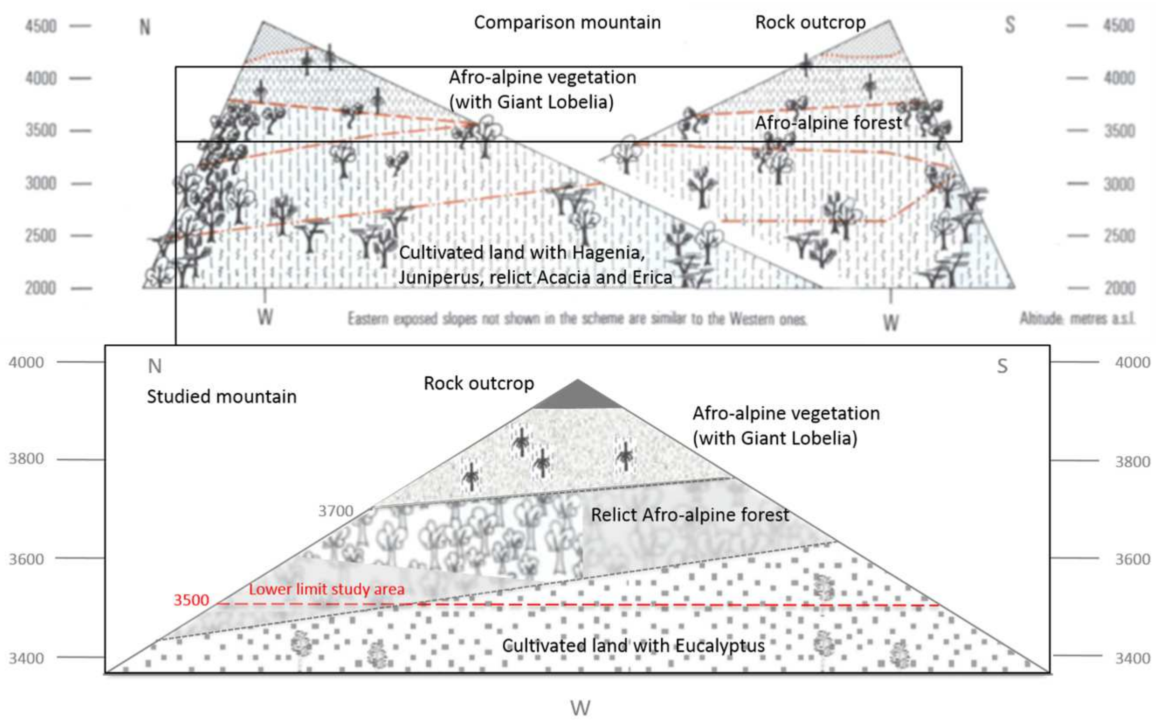

Figure 3.12 Contemporary altitudinal belts including degraded and disappeared *Erica* forest because of human disturbance, compared with current vegetation belts for the Simen Mountains (top figure by Hurni (1981).

Contemporary altitudinal belts consist of *Eucalyptus* and cropland in the lower belts and degraded *Erica* forest and afro-alpine grassland with typical shrub species and *giant lobelia* (Figure 3.12). No current periglacial belt is represented because current solifluction processes were not observed.

3.4 Discussion

3.4.1 Landform genesis: glacial and periglacial features

Avalanche-fed glaciers

Morainic ridges were found in the study area of Abuna Yosef. Because a cirque is not present and the calculated avalanche ratio suggest the importance of avalanches for glacier survival (Table 3.3), a small avalanche-fed glacier is suggested to have caused these features. The clear ridges present at the sites exclude a regular rock fall origin. The present of a fine matrix in the morainic material and the clear difference between the less blocky depressions and the blocky outer boundaries of the sites also exclude possible existence of a rock glacier. Present analogues of AFGs are found elsewhere in marginal glacial environments (e.g., Hughes, 2007; Carturan et al., 2013). For example, the lowermost glacier in Italy is fed by avalanches from high rock walls, which also reduce ablation of the glacier by topographic shading and supplying debris. Thus, local topo-climate conditions allowed the existence of such glaciers, much below the climatic ELA. Evidence is also given by Hurni (1982), who observed similar morainic features on the Silki Mountains, formed by snow accumulation rather than ice formation. Although these local avalanche-fed glaciers are marginal, they leave large morainic ridges (Carturan et al., 2013). The summits of the Abuna Yosef range may have been lower than the modeled Pleistocene ELA (4100–4400 m; (Hurni, 1981), still an avalanche-fed glacier existed because of local topo-climate conditions. In total, three sites in the Abuna Yosef massif have been recognized to bear evidence of small avalanche-fed glaciers. All sites are located on northwest- to northeast-facing slopes and are overshadowed by a steep ridge, the Abuna Yosef plug (site 1), or structural relief (sites 2 and 3). These uphill slopes are considered potential avalanche contributors because they are steeper than 30°. Site 2 has the biggest avalanche ratio (3.03), where the potential snow contribution by avalanching is three times the area of the former glacier. At site 3 the potential snow contribution by avalanching is two times the area of the former glaciation. Only at site 1 is the avalanche contribution area less than one time the area of the former glacier. This could be caused by overestimation of the glacial extent given the disturbance of recent rock fall. Nevertheless, only the avalanche areas were taken into account. Snow could also have been windblown from the plateau situated to the south of the sites (Figure 3.5). If this was the case, the plateau would have been an enormous source for snow for all the AFGs sites. Thus snow input from avalanches and windblown snow must have been crucial for the formation of small marginal glaciers in the Abuna Yosef massif. The big angular blocks in the moraines were interpreted as frost-weathered rock because of typical straight, smooth surfaces with sharp edges. The blocks did not show any evidence of striations or other indications of glacial transport. However, no other hypothesis can explain the formation of these ridges and natural depressions. If a small marginal glacier occurred in the shadows of these steep structural escarpments, the glacial transport was possibly so short it did not leave any striation marks on the rocks. Striations are also not likely to be conserved on basaltic rock (Hurni, 1981). These marginal glaciers often have a debris cover, originating from frost weathering of the overhanging bedrock (Carturan et al., 2013; Hughes, 2007). If this was the case in the study area, this could have favored the marginal glacier occurrence even more given the isolating properties of the debris cover. This could also explain the relatively large ridges, consisting out of large angular blocks without striations. The blocks would have been transported on the surface of the small marginal glacier, originating from frost weathering of the overhanging structural escarpment.

Solifluction and fluvio-solifluction lobes

Current solifluction activity in the Simen Mountains is present at an altitude of 4200–4250 m (Hastenrath, 1974; Hurni, 1981). Because this altitude exceeds that of the study area and solifluction lobes are observed down to 3600 m, the solifluction lobes are considered inactive and dating from the LGM. Other indications of their inactivity are the presence of abundant vegetation, which indicates a stable environment (Hastenrath, 1974; Grab, 2002), and the fact that road cuts across the lobes were observed to be stable.

The solifluction lobes in our study area consist of sorted periglacial rubble: angular clasts that are oriented downslope and are often embedded in a yellow-brown matrix of loamy silt. This is in line with observations in other North Ethiopian mountains (Williams et al., 1978; Hurni, 1981; French, 1996). The periglacial material in the valley NW of Lib Amba can be interpreted as fluviosolifluction deposits because of a sandier matrix and less angular stones in the profile. The post-LGM river working has incised through the material. Similar observations were made in the Simen Mountains by Hurni (1981). However, interpretation by using a clast shape should be made with caution. Angularity of the deposits clasts is a questionable indicator for freeze-thaw weathering, because the landform is a product of the interaction between both the geomorphological process and the initial material (Hall and Thorn, 2011). Here, the initial material is basalt, characterized by a typical spheroidal weathering. Angular weathering of basalt has been recognized as frost weathering in other North Ethiopian mountains (Williams et al., 1978; Hurni, 1981; French, 1996).

Although northwestern slopes bear significantly more solifluction and fluviosolifluction lobes in Lib Amba, all different aspects are represented in the data set. This is not the case in Ferrah Amba where such lobes occur exclusively on north and northeastern slopes, indicating that solifluction processes was restricted to the colder slopes. The environment was not cold enough to create periglacial landforms on slopes with less favourable aspects, similar with observations made in Lesotho (Grab, 1999). However, solifluction lobes in Ferrah Amba can only be found on slopes with less pronounced structural cliffs. Formation of solifluction lobes would have been constrained by these cliffs on other slopes. Less pronounced cliffs on slopes with solifluction lobes could also be a result of this solifluction process, because of coverage by soil movement. Further investigations are needed to explore these hypotheses.

3.4.2 Patterned ground phenomena

Patterned ground and solifluction lobes can be indicators of seasonal frost and permafrost, so they cannot be used as unambiguous permafrost indicators. However, well-developed landforms are often associated with permafrost (Etzelmüller et al., 2001). Only micro-patterned ground phenomena from contemporary frost action were observed in the study area. It is possible that no large-scale polygon-patterned features were found in the study area because of erosion and slope action after the last cold period. However, large polygon-patterned features were observed in the Bale Mountains (Grab, 2002; Miehe and Miehe, 1994). This suggests that no or only local permafrost was present in the study area during the LGM. While in the Bale Mountains, current frost action is present down to 3200 m (Miehe and Miehe, 1994), current frost cracks occur down to 3600 m in the study area. This altitudinal zonation difference clearly shows the difference between the current prevailing climates in these two mountainous areas. Possibly this was also the case during the LGM, explaining the absence of permafrost in the study area. In the Abuna Yosef, more pronounced frost cracks were observed near streams, ranging in the metre scale. This is in agreement with observations of French (1996) and Grab (2002).

3.4.3 Glacial and periglacial landforms and their implication for paleoclimate reconstructions

Interpolation of observations in the Bale and Simen Mountains showed that the lower limit of present periglacial processes exceeds the altitude of the study areas (Figure 3.13). Altitudinal belts for LGM and the present are similar for all three study areas. Figure 3.13 also shows that the observations made in this study are in line with the other observations around those latitudes concerning lower limit of periglacial processes during the LGM.

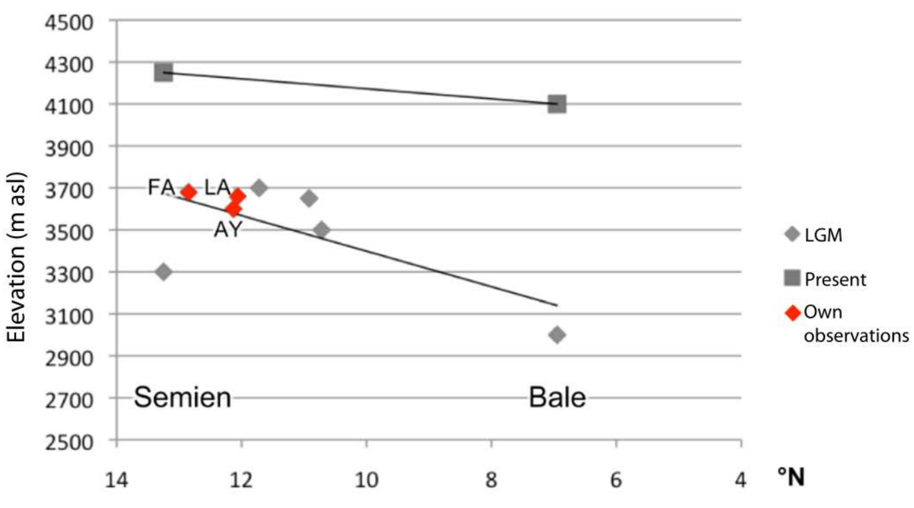

Figure 3.13 The lower limit of the periglacial processes during the LGM and at present in Ethiopia by latitude is shown based on findings by Scott (1958), Hastenrath (1974), Messerli et al. (1977), Williams et al. (1978), Hurni (1989), and Grab (2002) and our observations (FA = Ferrah Amba, LA = Lib Amba, AY = Abuna Yosef)

The ELA is often used for paleoclimatic reconstructions and can be calculated from elevation of morainic material (Nesje and Dahl, 2000). However, only in the study area of Abuna Yosef was morainic material of avalanche-fed glaciers found, typically formed below the modelled ELA due to local topo-climate conditions (Hughes 2007; Carturan et al., 2013). Since the periglacial belt is parallel to the ELA (Hurni, 1981), the altitudinal differences between the past lower limit of the periglacial belt and the present lower limits of periglacial processes can be used to reconstruct the paleoclimate.

In the study area, temperature dropped around 6°C (Figure 3.14). This is less than the temperature drop of 7°C based on geomorphological evidence and calculated by using the dry adiabatic lapse rate for in the Simen Mountains by Hurni (1981). Since the study area is lower in altitude, a less pronounced cooling is expected. The highest study area, the study area of Abuna Yosef, also experienced the greatest altitudinal depression (Figure 3.14). Higher mountains are more sensitive to climatic changes and experience larger shifts in altitudinal belts (e.g., Haeberli and Beniston, 1998). The temperature depression computed for the study area is in the same order of magnitude as those observed elsewhere in East Africa (Hurni, 1981; Osmaston and Harrison, 2005; Osmaston, 2004)

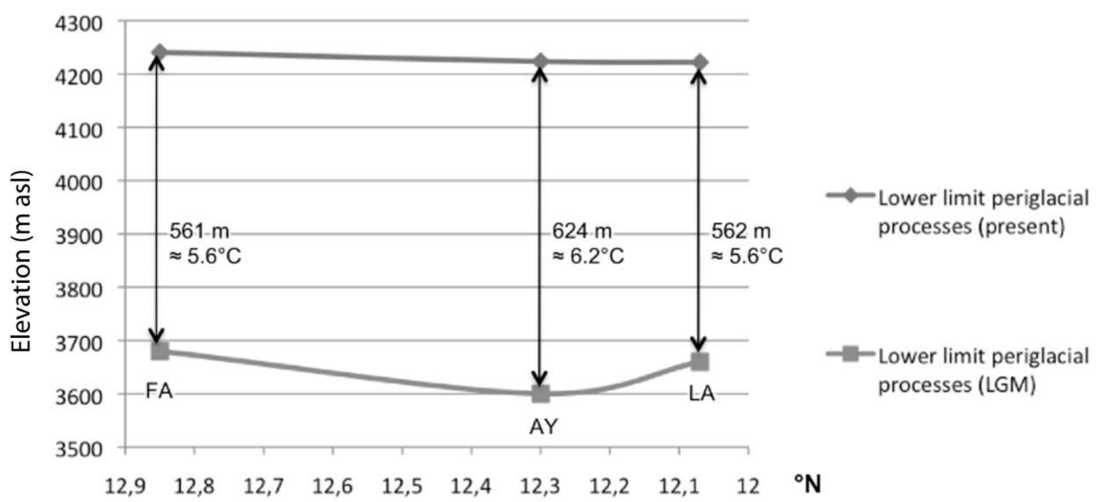

Figure 3.14 Altitudinal depression of periglacial processes in the study areas (FA = Ferrah Amba, LA = Lib Amba, AY = Abuna Yosef). Limit of present processes is interpolated from observations in the Bale and Simen Mountains; limit of LGM processes from field observations.

3.5 Conclusion

This study focuses on three mountain areas in the highlands of North Ethiopia (total area of 47.3 km^2) for which glacial and periglacial research has never been done. Geomorphological mapping with focus on these landforms was conducted in the study area of Abuna Yosef, Lib Amba, and Ferrah Amba. The produced map is not only the first geomorphological map of the study area but also one of the very few maps with a focus on glacial and periglacial morphologies in the Ethiopian highlands. Because (peri)glacial research is limited in the intermediate mountains (3500–4200 m) in Ethiopia and other tropical mountains with similar environmental conditions, the study area can be seen as a representative case study for all intermediate mountains in the tropics. In the high mountains of Ethiopia (above 4200 m), evidence of past small glaciers is present in the Bale, Arsi, and Simen Mountains. Although the study area lies entirely underneath the modeled equilibrium line altitude (ELA), small marginal glaciers are suggested to have existed in the upper north-facing slopes of the Abuna Yosef range in the absence of more substantive evidence. These glaciers were fed by avalanches and overshadowed by steep slopes and the ELA was depressed locally. Frost-weathered debris from the overhanging cliffs formed an isolating layer on top of the glaciers and made distinct morainic ridges with large angular blocks. Thus, local topo-climate conditions ensured the existence of these glaciers, presumably dating from the LGM although absolute dates are lacking.

In the other parts of the study area, no morainic material was found but solifluction lobes and fluviosolifluction material are present. Although absolute dates are lacking, all these landforms are assumed to date from the Last Glacial Maximum (LGM) based on similar observations in nearby mountain areas. Contemporary frost action could be observed in the form of small-scale patterned ground phenomena. Needle ice was not observed because the timing of the fieldwork was not ideal for observing this phenomenon. Compared with the Simen Mountains, similar contemporary and LGM altitudinal zonations occur in the study area, but are located 100–200 m higher than in Simen. Solifluction lobes do not reach as far down, and a glacial belt is not present in Lib Amba and Ferrah Amba. Current solifluction processes do not occur in the study area. This has implications for paleoclimate reconstruction. A temperature drop around 6°C was calculated for the LGM in Ferrah Amba, Lib Amba, and in the Abuna Yosef range. This is less than the temperature differences reconstructed for the Simen Mountains and explains the altitudinal differences of the belts of around 100–200 m.

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Chapter 4 Physiognomy of afro-alpine forests under different growing conditions in North Ethiopia

Abstract

Overall, forest management in Africa south of the Sahara is constrained by insufficient knowledge about the condition and structure of the forests. In this chapter, the stature and treeline structure of the *Erica arborea* forest is explored for different elevations and growing conditions in the North Ethiopian highlands. A comparison is made between (i) the lightly logged forest in Lib Amba Mt. and the heavily logged forest in Ferrah Amba Mt. and (ii) tree growth in the central forest and at the stress-exposed treeline. The forest stature is described based on exploratory plot measurements of the trees and forest indices; canopy cover, basal area, height diameter coefficient and tree life crown ratio. The treeline structure was analyzed from transect measurements across the treeline ecotone and by plotting a sigmoidal function through the tree-height elevation relation. These exploratory measurements indicate that the forest of Ferrah Amba Mt. is strongly disturbed, there are a high amount of tree stumps (app. 30%) and more than 50% of the trees are damaged. The forest canopy is low and average tree height is less than 2 m. This is the result of continued anthropo-zoogenic pressure, which degraded the Ferrah Amba forest to a dwarf forest. On the contrary, increased protection measures have proven successful in Lib Amba Mt. Average tree height is more than two meter, tree density is almost double and the forest canopy gives more than 50% cover. *Erica* growth at the treeline ecotone is indicated to be higher on gelifluction lobes than in the surrounding depressions, due to competition. This study indicates that there is a high need for improved forest protection in Ferrah Amba Mt., especially on the steep slopes, in order to allow a natural recovery of the forest. Such forest recovery is vital for a continuation and enhancement of the ecosystem services provided by afro-alpine forests.

Keywords: forest management, treeline structure, forest indices, competition

4.1 Introduction

The existence of a more luxuriant forest one hundred years ago in North Ethiopia has been disproven by Nyssen et al. (2009, 2014). The condition of woody vegetation and soil and water conservation structures were proven even worse at the early 20th century as compared to the present status (Nyssen et al., 2014). However, the upper afro-alpine forests are under-represented in such analyses. Statements about the afro-alpine forest are mainly derived from analysis in the protected environment of the Simen Mountains (Nyssen et al., 2014), while forest cover change studies in Lib Amba Mountain of the Abune Yosef Mts. indicate that the higher mountain regions were only recently colonized and that the forest is degraded due to intensified human pressure (Chapter 5). In general, forest management south of the Sahara is constrained by insufficient knowledge about the condition and structure of the forests (Hitimana et al., 2004). The same is true for the physiognomy of the afro-alpine forests in Northern Ethiopia. This is not without risk because the highland forests provide important ecosystem services to local communities and the environment (Bognetteau et al., 2007). These forests function as a hygric buffer, by capturing and storing rainfall, and benefit to the water balance of the mountain ecosystem and the agricultural areas in the surrounding lowlands (Aerts et al., 2002; Markart et al., 2007; Miehe and Miehe, 1994). The local communities are also highly dependent on these forests and directly impact them for their subsistence through livestock herding, fire and wood harvesting (Figure 4.1) (Boahene, 1998; Wesche et al., 2000). This descriptive chapter gives an exploratory insight in the physiognomy of the upper forest belt in the North Ethiopian highlands in association with different levels of forest degradation. The forest physiognomy is defined as “the form and structure of natural communities” (Oxford Dictionnary of Plant sciences, 2013).

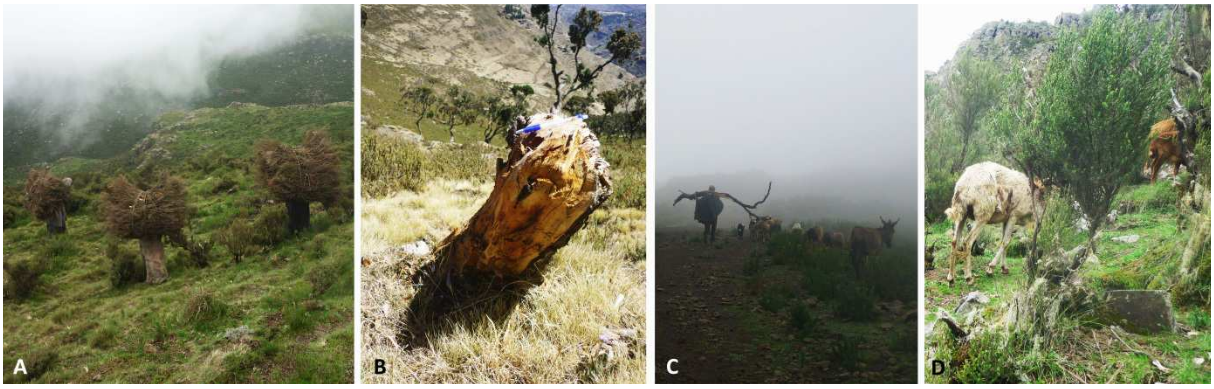

Figure 4.1 Anthropo-zoogenic pressure on the afro-alpine woody vegetation in the North Ethiopian highlands; (A) collection of tree branches (B,C) deforestation (D) livestock browsing.

4.2 Methods

4.2.1 Study area

This chapter studies two mountain forests in the North Ethiopian highlands under contrasting management conditions. Lib Amba (3993 m a.s.l.) of the Abune Yosef Mt. range which is completely protected since 2007 and Mt. Ferrah Amba (3939 m a.s.l.) which is weakly protected and continues to be strongly influenced by anthropo-zoogenic impacts (Figure 4.2).

Based on interviews with local guards in the study areas, the protection policy could be reconstructed. The northern forest of Lib Amba is strictly guarded; it is not allowed to graze and to cut any tree or branch in the forest. There is a team of 31 guards responsible for the protection of the forest. There are plans to exploit this area for tourism by attracting hikers from the nearby touristic center of Lalibela. The policy of Ferrah Amba on the other hand is less strict. The mountain is divided in five parts with in total 8 guards, only one of these parts is closed. In the other parts it is allowed to graze, to collect dry branches and possibly to cut a big tree or to prepare firewood for a ceremony (funeral/wedding). Moreover, illegal cutting is widespread because the guards are not well trained and under-represented.

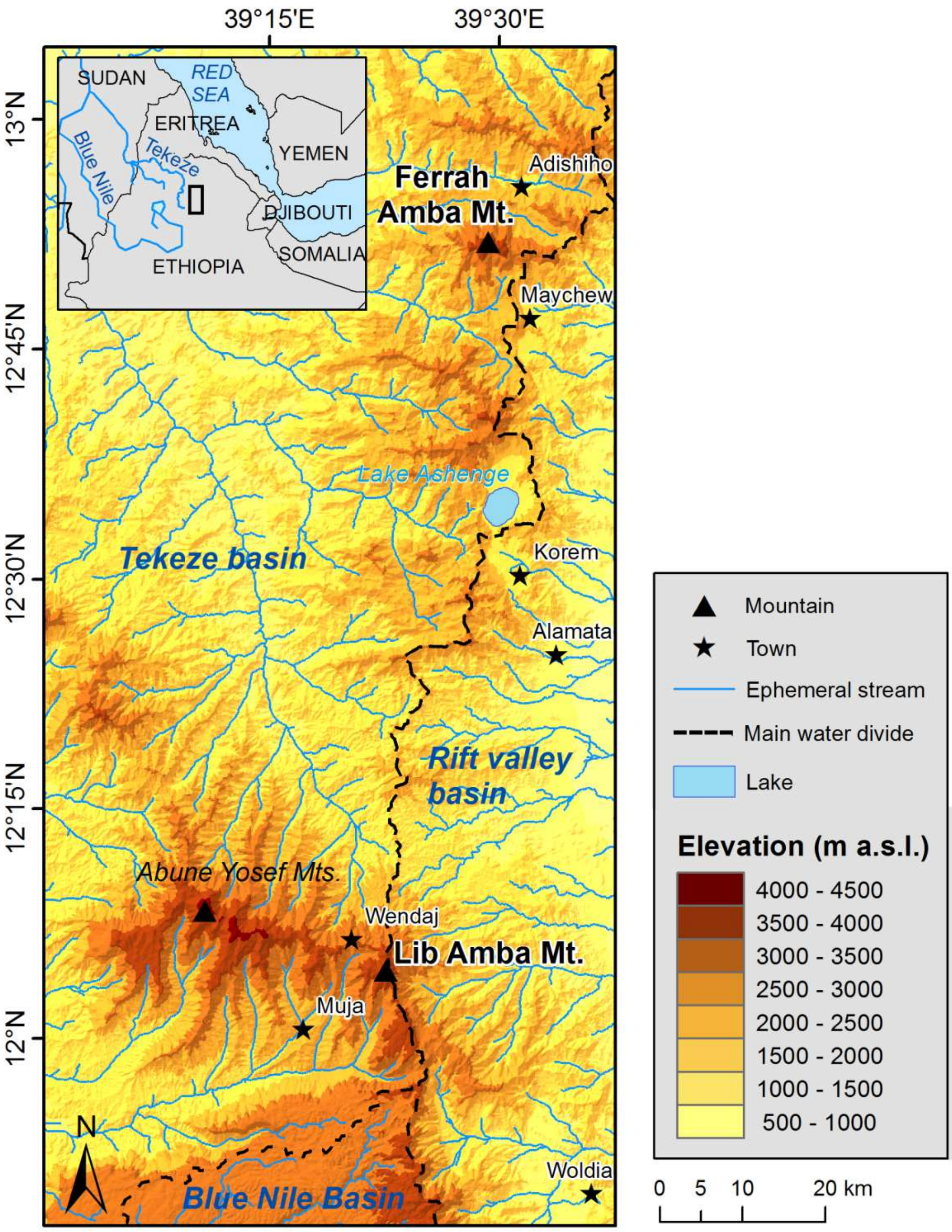

Figure 4.2 Location of the study areas

4.2.2 The afro-alpine belt

The limit of the afro-alpine belt is defined as the area higher than approximately 3200 m a.s.l. (Egziabher, 1988). Plants growing in this afro-alpine belt are exposed to intense radiation, due to the high altitude of this belt. This causes a stronger temperature gradient between the aerial and underground parts of the plant, with as result a higher transpiration than water absorption rate. Consequently, plants must be adapted to drought, despite the relatively wet conditions in the highlands (Egziabher, 1988). In adaptation to these conditions, plants are succulent (e.g. *Kniphofia* spp.), cushion forming or spinescent (e.g. *Helichrysum citruspinum*). Plants in the afro-alpine belt are therefore in general slow growing and low of stature (Egziabher, 1988).

Plant distribution is subdivided between slopes and flatter grounds, based on moisture availability. On the flatter ground, water ponds and water-loving species occur (e.g. *Ranunculus* spp.) (Friis et al., 2010). On slopes, moisture availability is lower, the vegetation consists of meadow grasses (e.g. *Festuca*), other herbs (e.g. *Trifolium acaule*) with patches of *Lobelia rhynchopetallum*, cushions of *Helichrysum citruspinum* and shrubs of *Erica arborea*. *Erica arborea* is especially extensive in the lower afro-alpine belt. When left unburnt, *Erica* grows to tree-size at this elevation, even on very thin soils (Egziabher, 1988). On areas with well-drained deep soils, at the lower limit of this belt *Hagenia abyssinica* trees are growing (Egziabher, 1988; Friis et al., 2010). Poor drained flatter areas are open and develop meadows and peat accumulation. The combination of frequent heavy rains and the steepness of the terrain makes this belt very vulnerable to water erosion and human interference (Lambin, 1997).

Nevertheless, this belt is a very important source of dry season water and the ericaceous forest in this belt is also important for many endemic animals such as the Walia ibex (*Capra walie*) and Mountain Nyala (*Tragelaphus buxtoni Lydekker*). The destruction and fragmentation of this forest has adversely affected the habitat of these species, putting their survival at risk (Alemayehu et al., 2011; Yihune et al., 2009). Another flagship species living in this habitat and on the edge of extinction is the endemic Ethiopian wolf (*Canis simensis*) (Tefera, 2011).

4.2.3 Forest sampling and measurements

The study areas were selected to represent different growing conditions of *Erica arborea* trees. As stated, the two mountains have different logging intensities and histories. The forest of Lib Amba is protected, while the forest of Ferrah Amba is exposed to continuous human interference. Tree characteristics were exploratory measured in two small plots of 100 m^2 in each of the two mountain areas (Figure 4.3, Table 4.1). In each study area, one plot was delimited in the central forest and a second plot at the (stress-exposed) treeline (Figure 4.4).

Figure 4.3 Position of the treeline plots (A) Ferrah Amba (B) Lib Amba. Inserted are detailed photographs of the treeline plot areas.

Table 4.1 Plot characteristics

	Central forest		*Treeline forest*	
	Lib Amba	*Ferrah Amba*	*Lib Amba*	*Ferrah Amba*
Latitude (lat)	12°04’44” N	12°51’53” N	12°04’40” N	12°51’45” N
Longitude (long)	39°22’21” E	39°28’60” E	39°22’25” E	39°28’58” E
Aspect	N	N	N	N
Altitude (m a.s.l.)	3664	3686	3711	3761
Slope gradient (°)	28	27	22	32

Traces of disturbances at the treeline were measured within these plots. Disturbances are defined as direct human damage of the trees by cutting branches or complete trees. This human impact is measured by counting the cuttings of branches and tree stumps within the tree plots. The result is represented by (a) percentage of tree stumps in the plot and (b) percentage of damaged trees in the plot. In addition, recruitment of *Erica arborea* trees at the treeline was measured along the physiognomic treeline with measurements in 31 small plots of 9 m^2 at 20 m intervals (Figure 4.4, R). In every plot, the density and tree height of individuals between 3 and 30 cm and the density of trees higher than 30 cm were measured.

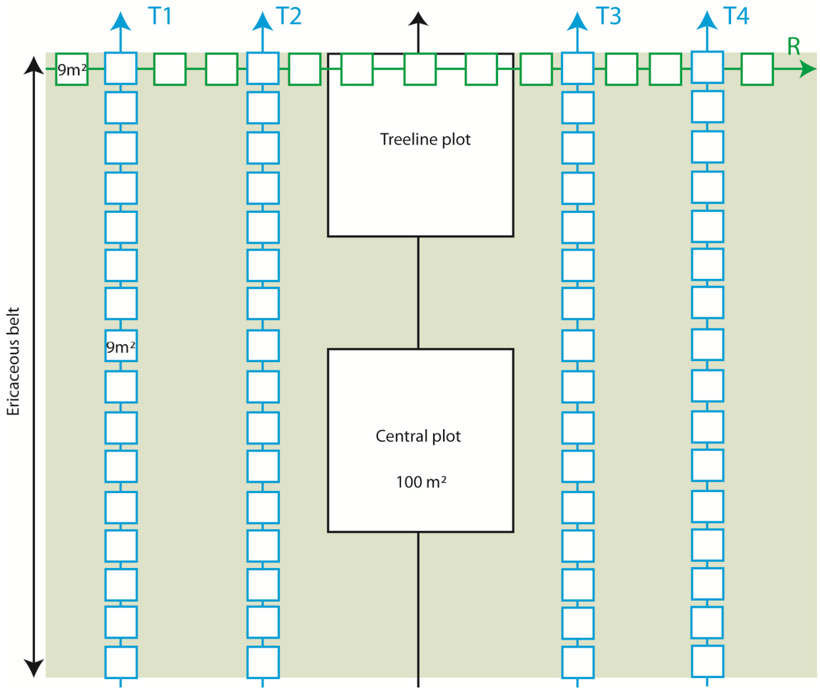

Figure 4.4 Schematic representation of the plot locations; (black) central and treeline plots of 100 m², (green) recruitment plots of 9 m² at the treeline and (blue) transect plots of 9 m² perpendicular across the forest.

The tree characteristics of *Erica arborea* trees measured in each plot are: (a) stand diameter, (b) stand basal area, (c) stand height and (d) stand density. The stand diameter (a) is, most commonly, measured at breast height. However, due to the bush size of trees at the treeline the diameter of the largest stem was measured at ground level. In forestry, the diameter is expressed as the Quadratic Mean Diameter (QMD); this is a measure for the diameter of the tree with the average per tree basal area (Curtis and Marshall, 1959). The basal area (b) is an important stand structure parameter. This parameter is calculated by summing the cross sectional area of the individual trees and is expressed by square meter per hectare (m²/ha). As mentioned, ground level diameter is used instead of breast height measurements. Because tree height in the study area is relatively low (less than 5 m), the stand height (c) was directly measured using a pole. The stand height can be expressed in different ways. Beside the simple average or median height, the dominant height, top height or Lorey's weighted mean height can be used to avoid the effect of thinning. For the calculation of Lorey's weighted mean height, the contribution of individual trees to the stand height is weighted by their basal area. Due to the high anthropo-zoogenic pressure in the study area, such advanced height expressions are preferred. The stand density (d) is derived from counting the trees within the plots and can be expressed as Trees Per Hectare (TPH).

Beside these stand parameters, the stand structure was further analyzed using the Height Diameter Coefficient (HDC), the Tree Live Crown Ratio (TLCR) and the Canopy Cover (CC). The Height Diameter Coefficient (HDC) is a ratio between height and diameter. This important parameter gives an indication of the structure and stability of the stand. Lower HDC values indicate small trees with a thick stem (Vospernik et al., 2010).

The TLCR is determined by dividing the live crown length by the actual length. This ratio is important because a bigger crown is related with better tree growth and a better ability to respond to improved competitive environments (O'Hara, 2014).

$$TLCR = \left(\frac{Live\ Crown\ Length}{Height}\right) \times 100$$

The Canopy Cover (CC) is the most important ecological variable of the forest. It is defined as the proportion of ground covered by a vertical projection of the canopy (Jennings et al., 1999). The canopy cover of each plot was measured using a vertical GRS densitometer, along two perpendicularly crossing line-intercept transects of 50 m (Stumpf, 1993).

Cautiousness is needed for the interpretation of these parameters. It is not possible to interpret the plot-derived parameters as absolute reflections of the vegetation physiognomy, due to the small sample size of the field plots. However, the representative location of the plots does allow a general and relative interpretation of the forest parameters.

4.2.4 Transect measurements

Treeline ecotones can be gradual transitions, abrupt boundaries, or patchy mosaics. The respective structures give an indication about the dynamic properties of the treeline (Bader, 2007). The treeline structure was measured at four vertical transects perpendicular to the forest boundary, crossing the treeline ecotone in both study areas. Along these transects the height and density of trees and tree seedlings was measured in 9 m² plots at 10 m intervals (Figure 4.4, T1-T4).

A natural ecotone is not a sharp boundary in the landscape, but a zone of gradual change. The vegetation within a natural ecotone becomes patchy in competition of resources at the margin of its environmental tolerance and gradually decreases. A gradual transition is best described with a sigmoid wave form (Cairns and Waldron, 2003). Subsequently, the treeline ecotone was described using a curve fitting method (Bader, 2007); a logistic function with height as a function of distance was used. In this model the steepness of the function is representative for the abruptness of the treeline.

4.2.5 Relationship between gelifluction lobes and tree growth

In the treeline ecotone of Lib Amba, tree counts were conducted to investigate the relationship between gelifluction lobes and *Erica* tree growth. In 42 plots of 25 m^2, the number of *Erica* trees were counted at different elevations along two gelifluction lobes and in between depressions at the northern slope of Lib Amba. In addition to the field counting, on screen photo counting was conducted from three extra gelifluction lobes and in between valleys. For both the field counting and photo-counting datasets, the amount of *Erica* trees was weighted with the area of the lobe or the depressions where they occur. The area of each depression and lobe is calculated in ArcGIS using zonal geometry from the Spatial Analyst toolbox. This way, the amount of *Erica* trees occurring can be expressed per hectare. Because the data is not normally distributed, a Kruskal-Wallis test is used to test the difference between vegetation occurrence on the lobe and in the valley between the lobes.

Because a difference in vegetation is often caused by different soil properties, soil thickness on the lobes and in the valley in between the lobes was measured. In each counting plot, an auguring was performed, two times at the top of the lobe and in the valley and two times at each side of the gelifluction lobe.

4.3 Results

4.3.1 Forest characterization for the study sites

The disturbance factors, tree stumps and tree damage, indicate anthropogenic induced disturbances in both study areas (Table 4.2). The northern forest on the Lib Amba Mountain is thus not a completely protected or undisturbed forest. Therefore, the forests are better re-categorized as “heavily logged” and “lightly logged” (Hitimana et al., 2004). As expected, human disturbances are especially high in the Ferrah Amba forest, with a high number of tree stumps (app. 30%) and more than 50% damaged trees in the central plot (% of total trees). At the treeline, the observed differences are less big for the disturbance factors, but they are more than double for the observed recruitment numbers. Recruitment in Ferrah Amba is thus inhibited.

Table 4.2 Disturbance and recruitment

	Central forest		*Treeline*	
	Lib Amba	*Ferrah Amba*	*Lib Amba*	*Ferrah Amba*
Total number of trees (N)	77	42	38	46
Disturbance				
Tree stumps (% of total trees)	8	30	12	20
Damaged trees (% of total trees)	41	60	18	18
Recruitment				
Average tree height (<30)[1](cm)			16.0	16.4
Tree density (<30)[1] (trees/m²)			12.8	5.5
Tree density (>30)[2] (trees/m²)			15.4	4.6

[1]Trees between 3 and 30 cm; [2]Trees above 30 cm

The effect of these different levels of forest degradation is reflected in the stand structure parameters. The central forest of Lib Amba is in a more natural state in comparison to the forest of Ferrah Amba. The weighted Lorey's mean tree height is more than 1 meter higher in Lib Amba, the forest is denser and the stand density is almost double (Table 4.3, Figure 4.5). The stand forest indices similarly indicate better growing conditions in the Lib Amba forest. The canopy cover, the basal area and the height diameter coefficient are almost double in Lib Amba. With other words, the central forest in Lib Amba is denser with bigger trees and a better-developed tree crown. The tree crown is an indicator of the health and vigor of the forest trees. The tree crown forms the structural architecture of the forest ecosystem and is important for the regulation of solar energy, nutrient recycling, precipitation distribution and moisture retention of a forest (Zarnoch et al., 2004).

Although tree height is significantly higher in Lib Amba, the quadratic mean diameter is not significantly different between the two study areas. This indicates that tree growth in Ferrah Amba is disturbed. Tree height is lower because trees are cut due to human interference, whereas the diameter at ground level keeps growing with a similar rate as observed in Lib Amba.

Table 4.3 Stand structure parameters

	Central forest		*Upper forest*	
	Lib Amba	*Ferrah Amba*	*Lib Amba*	*Ferrah Amba*
Stand parameters				
Trees per hectare (TPH)	7700	4200	3800	4600
Tree height (cm)				
Min	27	13	38	20
Median	223	125	103	105
Max	450	360	145	220
Average	225	127	99	100
Weighted Lorey's mean height	339	193	115	155
Top height (TH)	362	195	114	163
Dominant height (DH)	344	188	116	149
Diameter ground height (cm)				
Min	1.6	2.5	2.5	1.3
Median	7.0	7	5.1	4.8
Max	15.0	18.1	14.3	9.9
Average	7.2	7.2	5.6	5
Quadratic mean diameter (QMD)	8.1	7.9	6.1	5.4
Stand statistics				
Basal area (BA) (m^2/ha)	30.2	14.3	8.8	6.2
Canopy cover (%)	59	31	38	59
Height diameter coef. (HDC)	38	23	22	30
Tree live crown ratio (%)	43.6	68.4	79.7	84.6

The differences that we observed between the two sites in the central forest are not found at the treeline elevation. At the treeline, tree height is limited and trees are gnarled with umbrella shaped crowns in both sites. This is according to expectations because the vertical growth is increasingly limited by external factors (Körner, 2012). The treeline dwarf forests are the result of the harsh climate at the treeline (Holtmeier, 2009). The gnarled forest structure at the treeline affects tree height more than tree diameter (Körner, 2012).

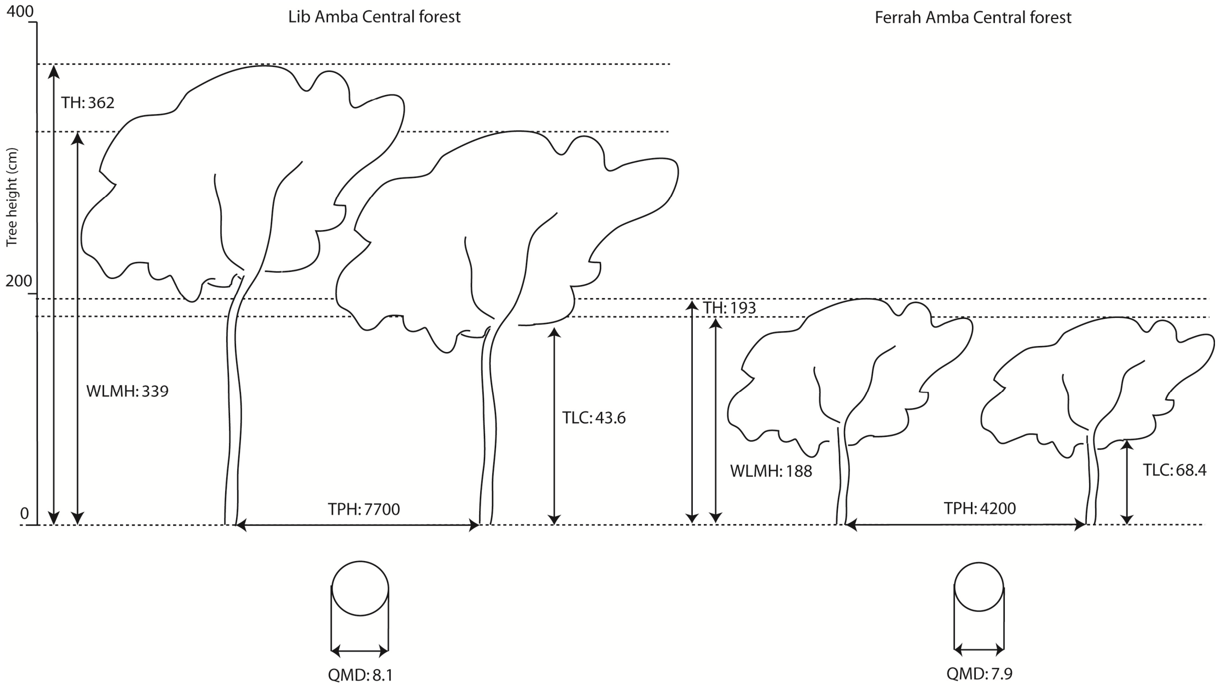

Figure 4.5 Comparison of the stand structure between the central forests of Lib Amba and Ferrah Amba

4.3.2 Treeline structure

The treeline ecotone shows an abrupt change in tree height for the two mountains (Figure 4.6). In Ferrah Amba this treeline shift is associated with the structural relief. Tree growth above 3790 m is depressed in height and limited in density. In Lib Amba this treeline shift is found at 3700 m. However, tree density of shrub-size trees above the treeline shift is especially high in Lib Amba. Tree height is highest at the steepest parts along the treeline ecotone.

The transition in vegetation height is expected to follow a sigmoidal pattern in natural conditions (Cairns and Waldron, 2003). The treeline ecotone in both Lib Amba and Ferrah Amba Mt. can be significantly fitted by a sigmoidal curve ($p<0.05$) with a coefficient of determination (R^2) of respectively 0.62 for LA and 0.58 for FA (Figure 4.7). In both mountains, tree height sharply declines at the treeline elevation. In Ferrah Amba, there is a gap with no measurements between approx. 3750 and 3800 m a.s.l., this is due to the structural relief of the mountain, above this elevation tree growth is very small (<1 m).

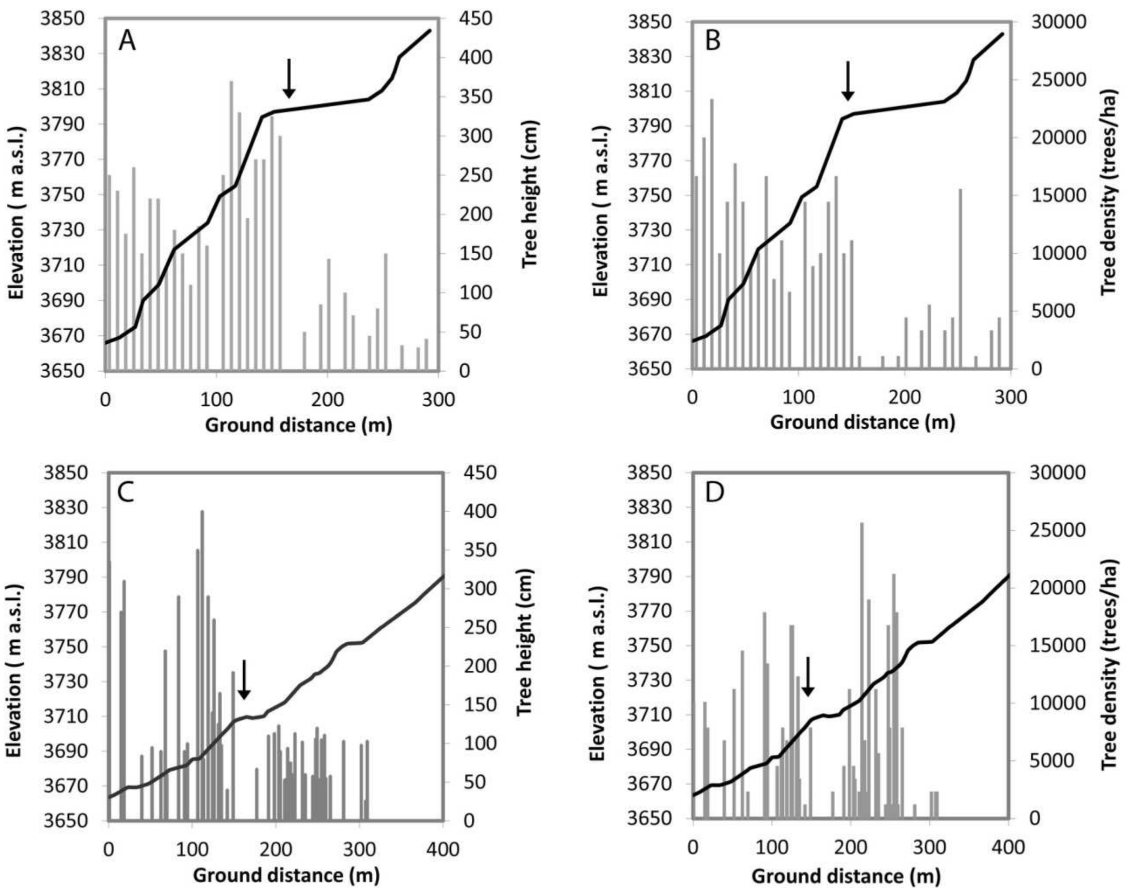

Figure 4.6 Maximum tree height and tree density in association to the topography as shown by a topographic profile. Arrows indicate treeline boundary shifts. Respectively, Ferrah Amba (A, B) and Lib Amba (C,D).

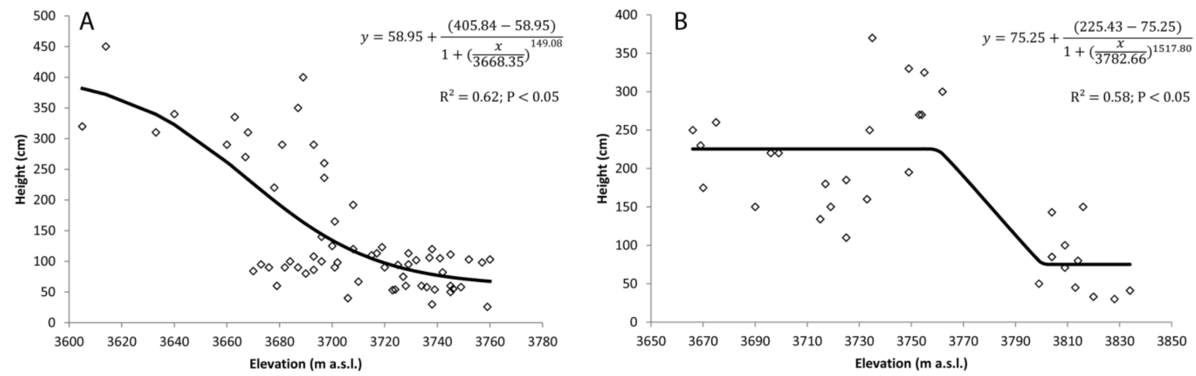

Figure 4.7 Sigmoidal function fitted through tree height of *Erica* trees along the treeline ecotone (A) Lib Amba and (B) Ferrah Amba.

4.3.3 Preferential tree growth in the treeline ecotone

The occurrence of *Erica* individuals is indicated to be significantly different between gelifluction lobes and depressions (Kruskal-Wallis, $P<0.05$). On the lobes a mean of 36 individuals per hectare are found in the treeline ecotone, whereas only a mean of 13 individuals per hectare are found in the depression. This difference can be potentially explained by differences in soil thickness. Measurements of soil thickness of gelifluction lobes in Lib Amba and Ferrah Amba were indicated to be significantly different. More soil cover is observed in the depression and at the side of the lobe (Figure 4.8).

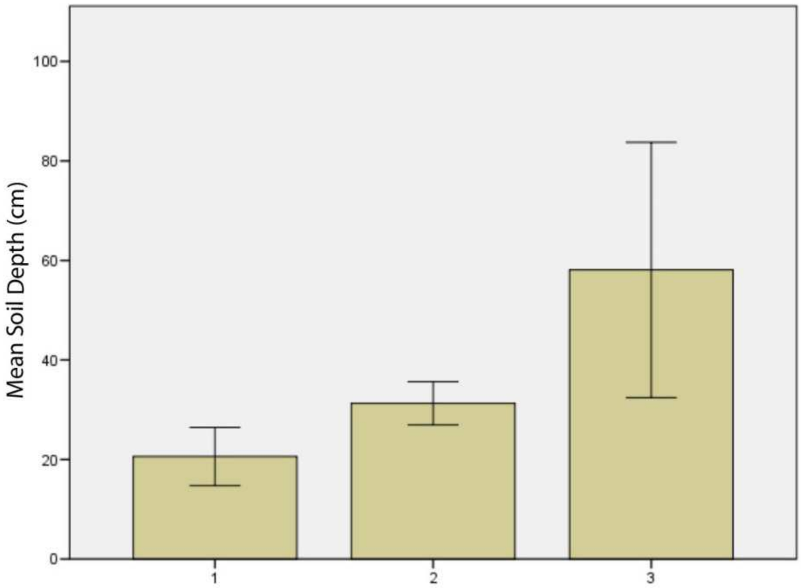

Figure 4.8 Soil depth in relation to gelifluction lobes in Lib Amba (1: on the lobe; 2: on the side of the lobe and 3; in the depression). Soil depths are derived from 70 augurings, of which 16 on top of the lobe, 27 on the side of the lobe and 27 in the valley.

4.4 Discussion

The harsh environment at the afro-alpine belt and the site-specific conditions are reflected in the physiognomy of the high altitude trees near the treeline (Holtmeier, 2009). Average tree growth at the treeline elevation is less than 2 m in both sites. Trees at the treeline are more exposed to climatic influences (wind, radiation, frost and others) and as a result tree height and annual growth decreases. *Erica* trees at the treeline form multi-stemmed stunted growth forms, also known as “dwarf forests” (Miehe and Miehe, 1994). However, these scrub-sized trees are considered part of the upper forest (Brass, 1964).

At the central forest of Ferrah Amba the limited tree growth (less than 2 m) is not climatic induced, but the result of high anthropogenic pressure. Tree stumps are widely observed (app. 30%) and more than 50% of the trees show evidences of human induced tree damage. Moreover, the use of the term ‘forest’ for tree growth in Ferrah Amba is not appropriate according to a strict interpretation of the definition of a forest (with a 3 m minimum limit) (FAO, 2010). However, this scrub-size of the forest is caused by human disturbance and for this reason the term ‘forest’ is used in this chapter.

Anthropo-zoogenic forest pressure is caused by a high need of the local population for wood products. Local communities are dependent on forest products for their subsistence and the lack of open natural forests causes this overall human pressure. The intensified pressure on the afro-alpine landscape causes an increased degradation of the landscape. One of the key elements for sustainable land management is the creation of forests at critical locations. Especially, the steep slopes must be protected to ensure water in downstream sources in the dry season and the reduction of soil erosion (Egziabher, 1988).

Forest recovery in Ferrah Amba is thus vital for a continuation and enhancement of the ecosystem services provided by afro-alpine forests. Such increased protection measures have proven to be successful in the northern forest of Lib Amba Mt. Average tree growth is more than one meter higher in Lib Amba, tree density is almost double and the canopy cover is much higher in Lib Amba. These measurements clearly indicate the healthier status of the forest in Lib Amba. However, this had repercussions for the southern forests of Lib Amba Mt., which are intensively disturbed and degraded to remnant forest (Chapter 5). Livestock pressure is high in Lib Amba (Figure 4.9) and shifted to the surrounding areas in response to the forest closing. Sustainable management thus implies a region-wide vision and reserving open areas for the local communities.

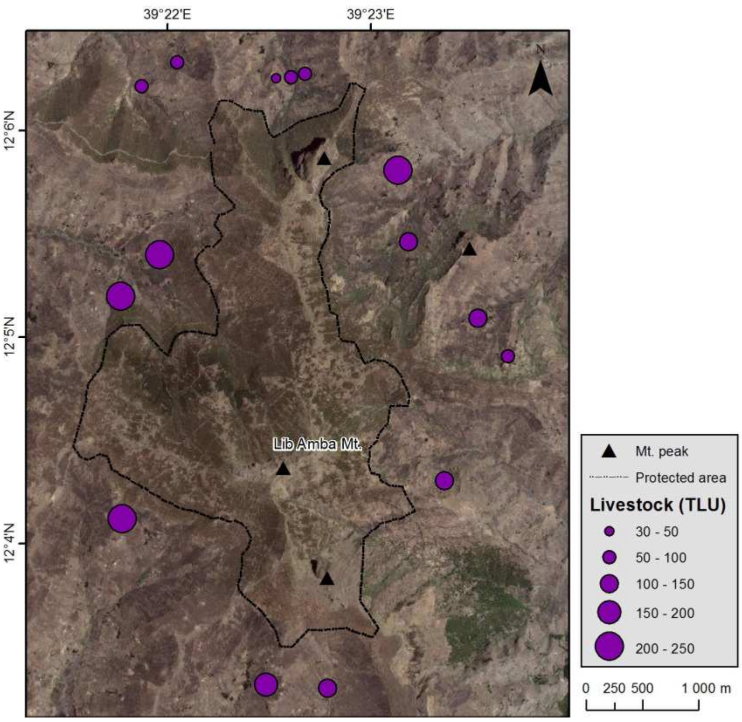

Figure 4.9 Livestock distribution spotted in Lib Amba on 14 September 2012. The graduated symbols show the Tropical Livestock Units (TLU) for the neighboring villages around Lib Amba Mt. The TLUs are summed for all livestock animals. The livestock numbers are visually counted on 14 september 2012 by Gashaw Derebe.

Erica individuals at the treeline ecotone grow more abundantly on gelifluction lobes than in the moist depressions in between (Figure 4.10). Investigations towards soil thickness revealed a thicker soil cover at the lower sides of the lobes and in the depressions in between. This soil thickness distribution can be explained by soil wash because of heavy rains. Soil erodes on top and accumulates at the sides of the lobes. This can also explain the more abundant vegetation in the valleys and the more frequent occurrence of grasses on the lobes (Figure 4.10). The observation of more *Erica* on the lobes seems in contrast with the apparently more favourable conditions (more soil and water availability) in the depressions. Competition is proposed in order to explain this contradiction. Two ecological theories about competition can be applied. The C-R-S theory, first introduced by Grime (1979), states that competition intensity is positively correlated with habitat productivity, resource abundance and neighbor biomass. In general, afro-alpine environments will thus experience less competition compared with more biodiverse habitats. However, if we apply this theory on microscale, considering the top of the lobes as a more infertile and exposed habitat, more competition will take place in the depressions where the resources (water and soil) are abundant. Also, competition increases if the competitor increases (Grime, 1988, 1979) and there is clearly more vegetation in the moist depressions. The shrub *Hypericum revolutum* is very abundant, together with giant lobelia. This theory has as objections that it only focuses on resource demand and does not take resource supply into account. Therefore, the Supply-Demand (S-D) theory is proposed by Davis et al. (1998). Here, the net resource availability is important. In this study, the shrub *Hypericum revolutum* lowers the net soil and water availability for *Erica* shrubs by its abundance in the more favorable depressions. It seems that competition is a more limiting factor for *Erica* growth than soil and water limitations. Observations of *Erica* on very rocky slopes with thin soil cover confirm this hypothesis.

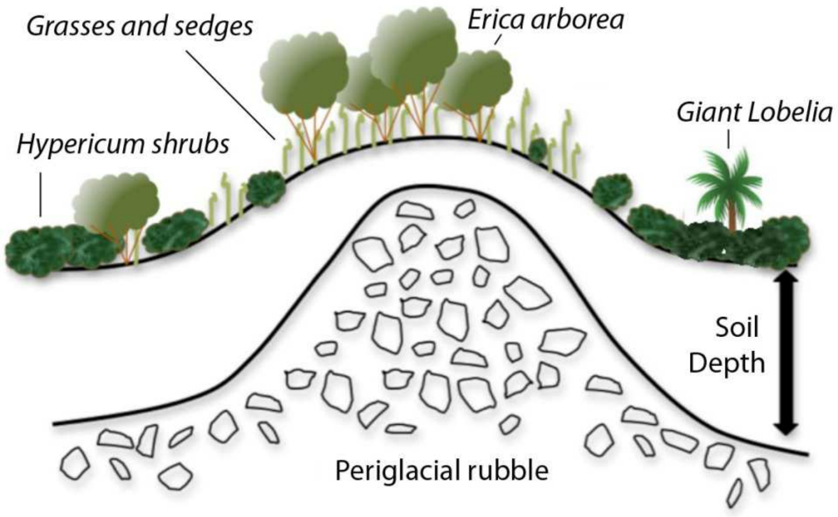

Figure 4.10 Schematic representation of the relationship between soil thickness and vegetation occurrence on a gelifluction lobe in Lib Amba

4.5 Conclusion

Tree characterization and transect measurements in the study areas give insight in the stature and structure of the *Erica arborea* forests under different growing conditions. The forest in Ferrah Amba is degraded under anthropo-zoogenic pressure to a dwarf forest. While the lightly logged forest in Northern Lib Amba is naturally growing with higher trees, with a higher canopy cover and subsequently a healthier natural forest status. This study indicates the need for improved forest management in Ferrah Amba mountain, taking into account the important ecosystem services of the *Erica arborea* forest for local communities, for wildlife species and against land degradation. In the treeline ecotone *Erica* growth on gelifluction lobes is more abundant then in the surrounding depressions, although more soil and water is available in the depressions in between. In the depressions, abundant vegetation is present, consisting out of *Hypericum revolutum* and Giant lobelia. Competition between *Erica* and these species is a more limiting factor for *Erica* growth than soil and water limitations. The introduction of protected forests is especially important on steep slopes. Moreover, increased forest protection is proven successful in the Northern forest of Lib Amba Mt. A sustainable management must thus be developed on a regional level and must also foresee areas open for the local communities.

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2013 1917

Part 2
Mapping treeline dynamics

The repeat photograph on the back of this page is taken from the southern slope of Lib Amba Mt. looking towards Aboy Gerey Mountain (3565 m a.s.l.). The 1917 photograph is taken by Conte Fillipo M. Visconti on an Italian trade mission from Leggu (Woldia) to Tembien (© Italian Military Geographical Institute) and the 2013 repeat photograph is taken during fieldwork on 12 July 2013. This 1917 terrestrial photograph gives a unique insight in the historical high altitude forest cover.

Chapter 5 Afro-alpine treeline dynamics and afromontane forest cover change since the early 20^{th} century – the Lib Amba case

This chapter is based on:

Jacob, M., Frankl, A., Beeckman, H., Mesfin, G., Hendrickx, M., Guyassa, E., Nyssen, J. (2015). North Ethiopian afro-alpine treeline dynamics and forest cover change since the early 20th century. Journal of Land Degradation & Development, online early view. DOI: 10.1002/ldr.232.

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 treelines in the tropics are scarcely investigated in comparison to higher northern latitudes. In this study, the *Erica arborea* treeline is studied in a tropical mountain in the North Ethiopian highlands: Lib Amba of the Abune Yosef Mt. range (12°04’N, 39°22’E, 3993 m a.s.l.). The present treeline 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 geometrically rectified and classified in forest/non-forest binary maps. The binary forest layers were used to detect forest cover change and treeline 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 protection of the afro-alpine forest and a population increase from 77 to 153 inhabitants per square km. There is significant evidence that the elevation of the *Erica arborea* treeline increased 7 to 15 vertical meter between 1965 and 2010, in an area with decreasing anthropo-zoogenic pressure.

Keywords: Treeline shift; Forest cover change; Land occupation; Climate change; Land management; Tropical highlands

5.1 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 km^{-2} in areas above 2500 m a.s.l. 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 not only important 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 and 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 (Descheemaeker et al., 2006; Nyssen et al., 2004).

The upper limit of these tropical high altitude forests forms one of the most apparent vegetation boundaries worldwide. The treeline 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 and Paulsen, 2004). Treelines are responsive to climate change (Körner and Paulsen, 2004), a change that is most prominent and rapid at high altitudes and latitudes (Holtmeier and Broll, 2005; Harsch et al., 2009). There are a growing number of studies about treeline dynamics in the tropics (e.g. Bader, 2007; Sassen et al., 2013; Wesche et al., 2008), but the response to climate change in the tropics and in the southern hemisphere is still scarcely investigated compared to treeline dynamics at higher northern latitudes (Holtmeier and Broll, 2007). At these high northern latitudes an average vertical treeline shift of 70 to 90 m occurred during the last century (Danby and Hik, 2007; Kullman and Öberg, 2009).

Improved understanding about treeline 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 understand the effects of climate change on these environments (Chapter 2).

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 twentieth 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 (Meire et al., 2013; Nyssen et al., 2009a). On the other hand, based on satellite images and aerial photographs, Tekle and Hedlund (2000) and Zeleke and 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 km² (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 (De Mûelenaere et al., 2014).

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

5.2 Materials and methods

5.2.1 Study area

The study area consists of Lib Amba Mt. and surrounding mountains (39 km², 12°8'N, 39°11'E, 3993 m) of the Abune Yosef Mt. range, part of the North Ethiopian highlands (Figure 5.1).

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; Nyssen et al., 2007). The high altitude soils are rich in organic matter and relatively acidic, the dominant soil type 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 5.1). It lies within the semi-arid to subhumid mountain climate zone of the North Ethiopian highlands (Nyssen et al., 2005) and rises above the present treeline at approximately 3700 m. The climate is characterized by unreliable seasonal rainfall, with annual rainfall ranging between 800 and 2200 mm year^{-1} (Chapter 7; 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 treeline ecotone in tropical mountains in Africa (Wesche et al., 2000). Hurni and Stähli (1982) identified four vegetation limits in the Simen Mts.: the Acacia limit at ca. 2730 m, the *Hagenia*, *Juniperus* and *Olea* montane forest limit at ca. 3200 m, the *Erica arborea* treeline 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 Mt., 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 *Erica arborea*.

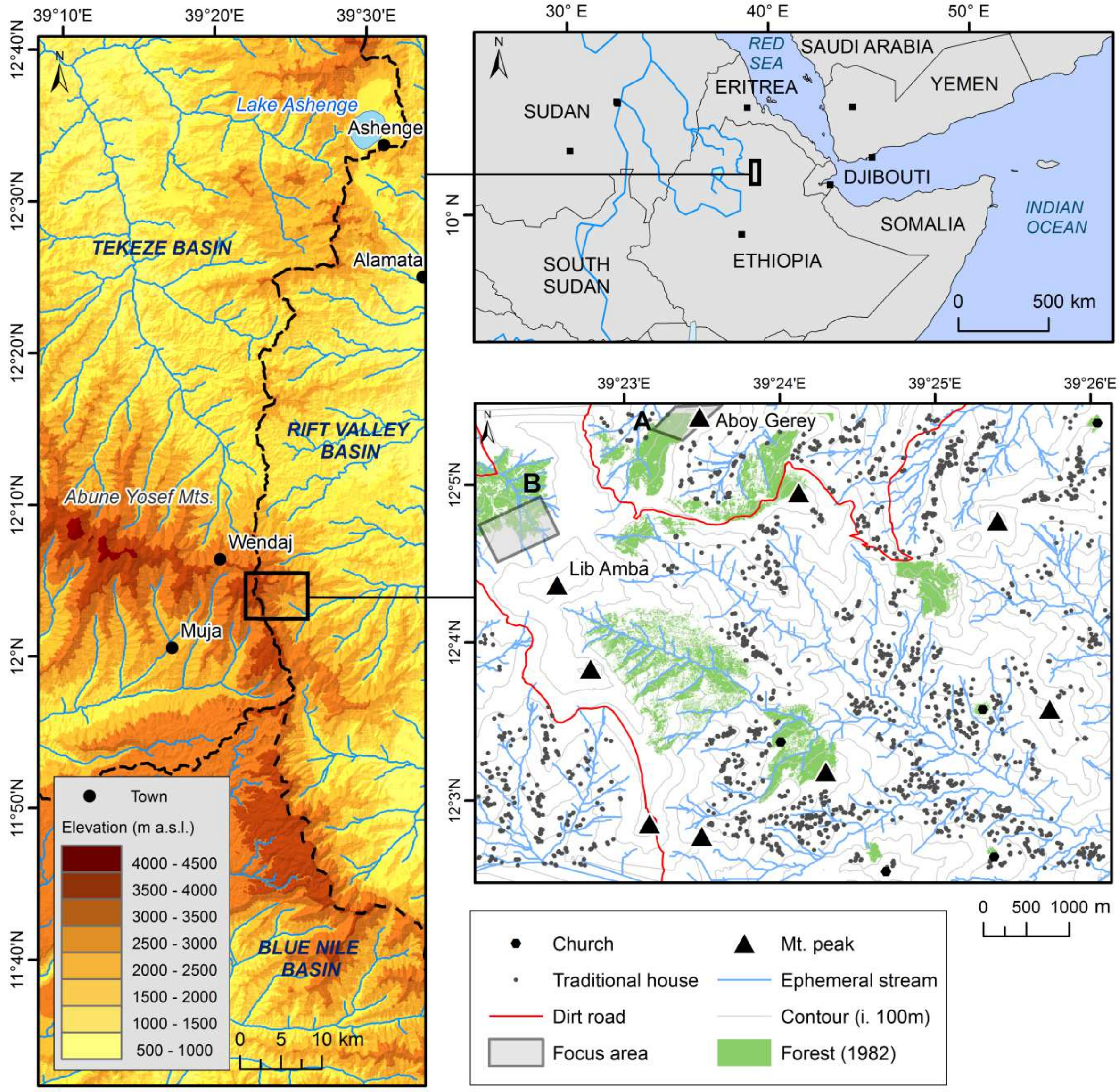

Figure 5.1 Abune Yosef Mountains and selected study area. In-depth focus areas: (A) repeat photograph of Aboy Gerey Mountain (B) treeline dynamics at Lib Amba Mountain.

5.2.2 Data and pre-processing

The oldest available data source providing information about the spread of high altitude forests in our study area (Figure 5.1A) is an historical terrestrial photograph of Aboy Gerey Mt. from 1917 made by Conte Fillipo M. Visconti © Italian Military Geographical Institute, Firenze.

Beside this terrestrial photograph, historical black-and-white aerial photographs of 1965 and 1982 (scale approx. 1:50 000, scanned at 1200 dpi) from the Ethiopian Mapping Agency (EMA) 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 (GNSS) measured Ground Control Points (GCPs) were used. In Table 5.1, the accuracy of the image orientation process is shown in terms of Root Mean Square Error ($RMSE_{xyz}$; 3.59, 4.80, 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 done 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 km². 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, Digital Globe satellite imagery (2010) was image-to-image co-registered with the 1982 orthophotograph as reference.

The accuracy of the co-registrations is tested by 10 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 significant different from that of the 1982 orthophotograph (Table 5.1).

5.2.3 Forest cover mapping

Repeat photography

Repeat photography is a very valuable tool for the study of the historical forest cover and treeline 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. (2013), Roush et al. (2007) and Frankl et al. (2012). In this study the approach of Meire et al. (2013) is used to warp the topographic forest unit from the terrestrial photograph on the orthophotograph.

Table 5.1 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)					
	N° of GCP	*RMSE[1] X*	*RMSE Y*	*RMSE Z*	*MAE[2] Z*	*LE90[3]*	*Software*
AP - 1982	14	3.585	4.799	5.7283	2.5047	3.4629	LPS[4]

Image-to-image registration (with the 1982 orthophotograph as reference)				
	N° of GCP	*RMSE X*	*RMSE Y*	*Software*
AP - 1965	150	3.559	4.818	ArcGIS
Google Maps - 2010	25	3.449	4.214	ArcGIS

[1] Root Mean Square Error
[2] Mean Absolut Error, the mean of the absolute value of the prediction error
[3] Linear Error 90%, error range which would include 90% of the pixels within the DSM
[4] Leica Photogrammetry Suite

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 treeline dynamics from black and white aerial photographs.

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. Secondly, texture information was computed for the masked aerial photographs (Erener and 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 (PCA) was applied to the raw texture images (Erener and 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 5.2).

In a third step a supervised Maximum Likelihood classification with three classes (forest, bush and grassland, cropland and rocks) was executed in ENVI (Figure 5.2). 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 the pixel is assigned to the class with the highest probability (Lillesand et al., 2008). Additionally, the classification was filtered with a 3x3-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 to study forest dynamics by post classification 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.

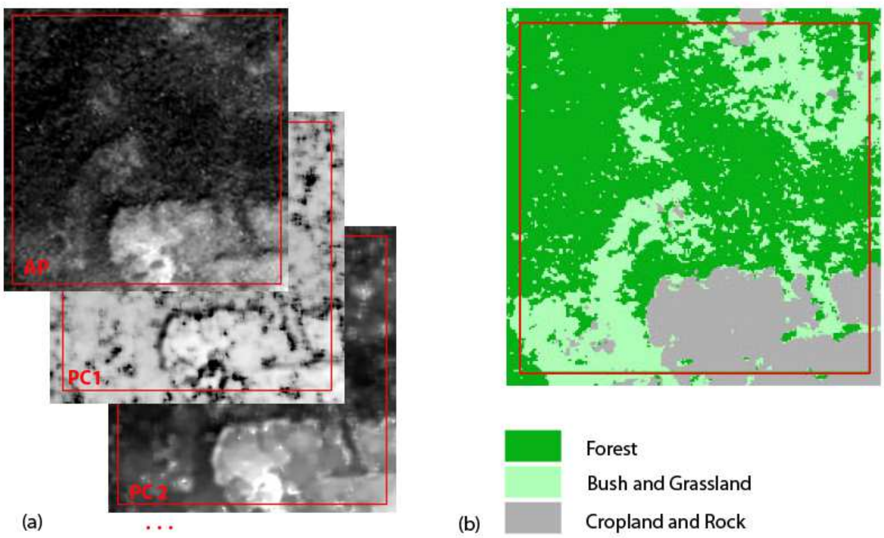

Figure 5.2 Schematic representation of the classification process: (a) Texture and PCA analysis (b) Supervised Maximum Likelihood classification

Treeline mapping

Treeline 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 5.1B). In this area and at this elevation the treeline is potentially limited by climate change.

The physiognomic treeline 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 x 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 treeline curve is smoothed in ArcGIS with the simplify line function (10 m tolerance). This smoothed curve is referred to as the envelope-treeline, because of the similarity with the geometrical envelope principle.

Application of this technique for the three layers allows detecting treeline change in the study area. Quantification of the changes is made possible by segmenting the envelope treeline in 10 m segments. The elevation of these segments are 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, since steep slopes are less accessible for anthropo-zoogenic 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°- 45° and >45° (Trejo and Dirzo, 2000).

5.3 Results

5.3.1 Classification accuracy

Accuracy assessment of the forest classification maps was done by using a random point sample design with a minimum of 50 samples for each class (Congalton and Green, 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 and 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 and Green, 2009). The Kappa value reflects the difference between actual agreement and agreement expected by chance, this value is high for the three classifications, respectively 0.79, 0.70 and 0.67. The classifications are thus reliable and in substantial agreement with the ground truth (Landis and Koch, 1977) (Table 5.2). 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 over-classification of shaded slopes in comparison to non-shaded slopes. But, 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).

Table 5.2 Accuracy assessment of the 1965-1982-2010 forest classifications based on confusion matrix derived measurers and Kappa values.

		Classified			*Omission*	*Overall*	*Kappa*
		forest	Non-forest	*Total*	*Errors*	*accuracy*	
1965 (AP)							
Ground truth	Forest	113	5	118	0.04	*0.90*	*0.79*
	Non-forest	14	63	77	0.18		
	Total	127	68	195			
	Commission Errors	0.12	0.07				
1982 (AP)							
Ground truth	Forest	99	1	100	0.01	*0.85*	*0.70*
	Non-forest	28	67	95	0.29		
	Total	127	68	195			
	Commission Errors	0.28	0.01				
2010 (SI)							
Ground truth	Forest	69	18	87	0.21	*0.84*	*0.67*
	Non-forest	13	95	108	0.12		
	Total	82	113	195			
	Commission Errors	0.15	0.17				

5.3.2 Forest cover dynamics

The early 20th century

Although we have only one historical terrestrial photograph for the study area, this photograph has proven important since it allows a unique comparison of the land cover over a period of almost 100 year (Figure 5.3). 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 upwards the mountain. Indicators of these changes are new settlements on the previously inhabited mountain slopes and cultivation terraces that reshaped the mountain flanks (Figure 5.3). 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 5.3). 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 Mt. (Figure 5.4). 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.

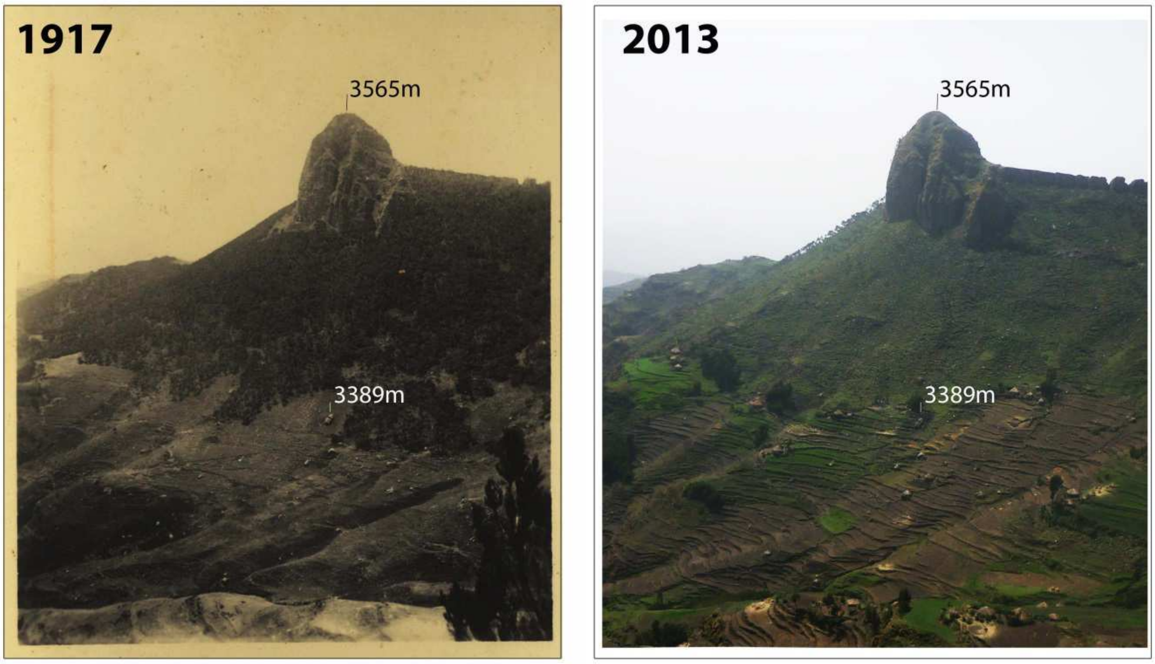

Figure 5.3 Repeat photograph of Aboy Gerey Mountain (3565 m a.s.l.); (left) historical terrestrial photograph of Conte Fillipo M. Visconti on an Italian trade mission from Leggu (Woldia) to Tembien © Italian Military Geographical Institute, Firenze; (right) repetition in 2013.

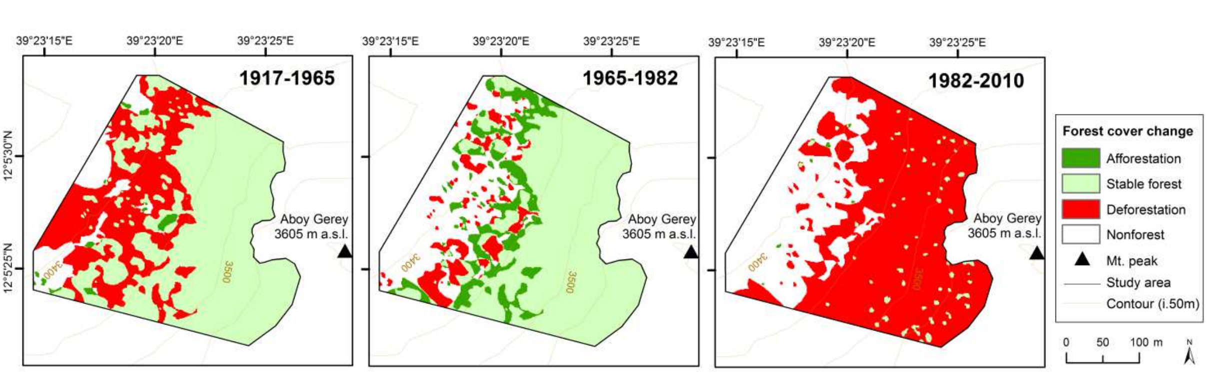

Figure 5.4 Forest cover changes on the western slope of Aboy Gerey Mountain in the period 1917–2010.

Between 1965 and 2010

Forest cover changes are shown by post classification comparison of the three forest cover maps (1965, 1982 and 2010) (Figure 5.6). 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 5.5). Deforestation mainly occurs at the edges of the forests, whereas there is an increase of the forest cover within the forest patches (Figure 5.5). 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 5.5). The forest expanded only in small patches. Whereas, outside these patches the forest disappeared almost completely (Figure 5.5).

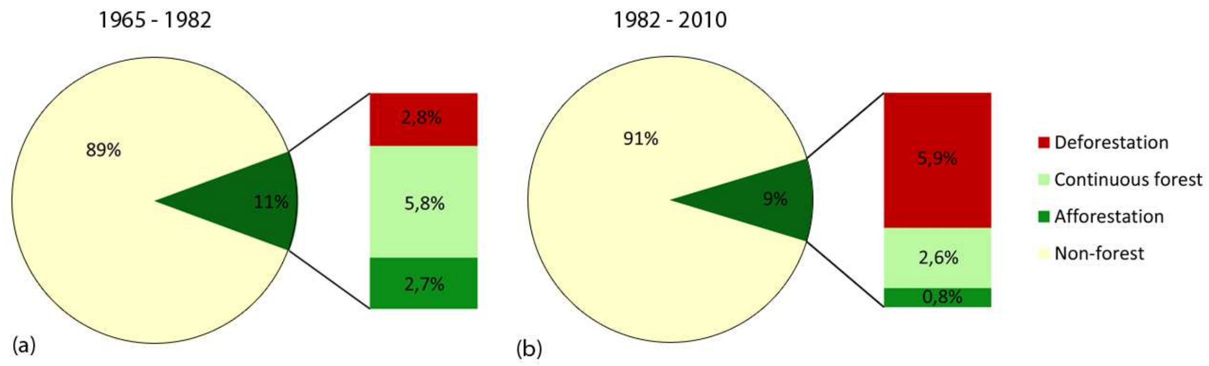

Figure 5.5 Percentage of forest cover change between (a) 1965-1982 and (b) 1982-2010.

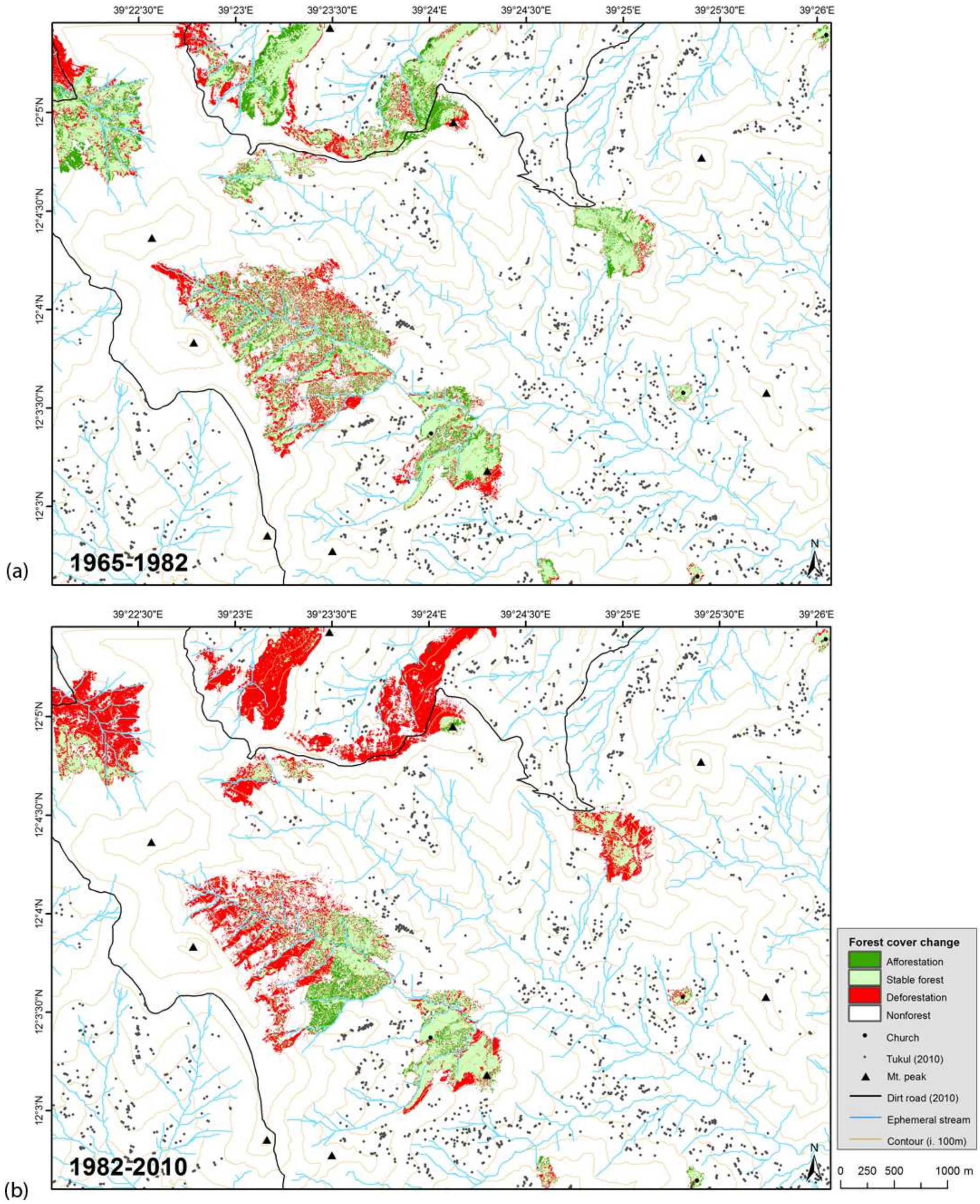

Figure 5.6 Forest-cover change between (a) 1965–1982 and (b) 1982–2010.

Treeline change

Mapping the envelope-treelines (1965-1928 and 2010) shows that there is an upwards trend of the treeline along the mountain slope in the west of the study area, while the treeline is comparatively stable at the steeper ridges in the east (Figure 5.7). Comparison of the average treeline elevation with a t-test between 1965 and 1982 indicates that there is no significant increase of the treeline. Between 1982 and 2010 there is a significant increase of the treeline between 6 and 13 vertical meter (Table 5.3). Over the full period 1965-2010 the treeline significantly increased between 7 and 15 vertical meter (Table 5.3).

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 treeline elevation in the three slope categories, but this treeline shift is much higher for the gentle slopes in the western part of the study area (Table 5.3).

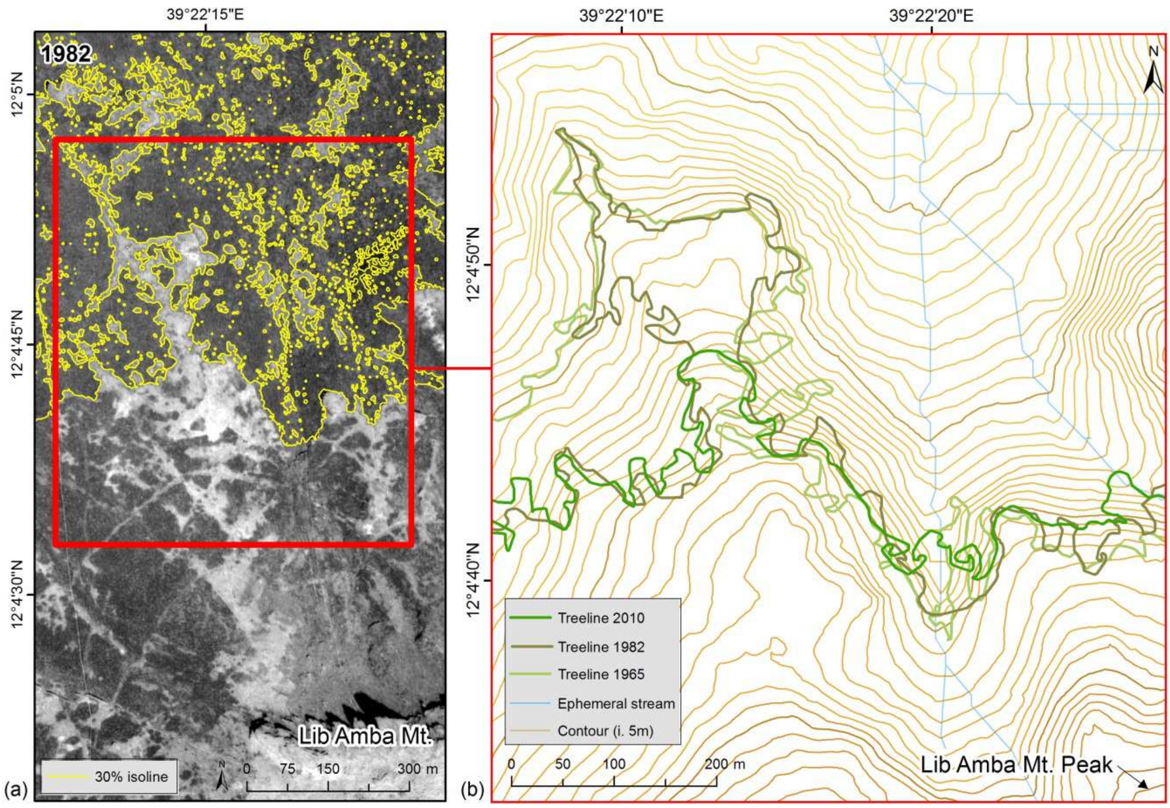

Figure 5.7 Treeline detection (a) 30% isoline and (b) detailed map of the derived treelines within the red subset: 1965, 1982, and 2010.

Table 5.3 A t-test comparison of treeline elevations between 1965-1982 and 2010 in order to identify potential treeline changes and slope effects.

	Treeline segments (10m)	*Treeline segments (N)*	*Q1*[1]	*Median*	*Q3*[1]
	1965	276	3651	3680	3703
	1982	286	3656	3684	3700
	2010	201	3681	3692	3700
	Treeline Change	*P-value*		*95% CI*[2]	
	1965-1982	>0.05			
	1982-2010	<0.05		6-13 m	
	1965-2010	<0.05		7-15 m	
	Slope categories	*Treeline segments (N)*	*Q1*	*Median*	*Q3*
All years	< 12°	74	3647	3659	3702
	12 < 45°	602	3662	3687	3701
	> 45°	87	3682	3692	3699
	Treeline 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	

[1]First quartile (Q1) and third quartile (Q3)
[2]Confidence Interval

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. Since, 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, show 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 anthropo-zoogenic 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 et al. (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

5.8). This increasing population pressure in combination with protection of the upper afro-alpine forest is potentially responsible for the observed deforestation trend.

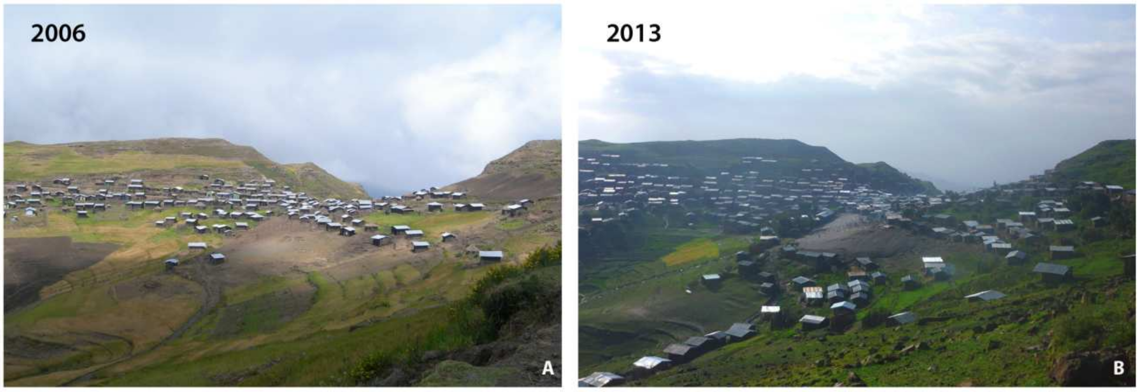

Figure 5.8 Repeat photograph of the expanding town of Wendaj (12°06'25"N, 39°20'18"E, 3478 m) at ca. 5 km (bird's eye view) to the west of Lib Amba Mt.; (A) on 26/10/2006 © CANN Panoramio; (B) on 13/07/2013.

5.4 Discussion

Long-term land cover changes are widely studied with Landsat images (Ouedraogo et al., 2010), but their 30 m resolution does not allow detecting small-scale changes. The proposed methodology for the detection of forest cover change and treeline dynamics allows detailed analysis of long term forest and treeline changes, from aerial photographs and recent satellite images. However, shading can cause over-classification of forest in comparison to non-shaded areas on the black and white aerial photographs. The classification could be further improved by eliminating the illumination effect, using a pixel based topographic correction derived from the DSM of the study area (Vanonckelen et al., 2013).

The use of aerial photographs to map forest cover also introduces a small over-classification 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 done by Brink and Eva (2009) for Africa. But the method is suitable for detailed forest cover and treeline dynamic studies.

In this specific study, the available information for the period before 1965 is limited, since there is only one historical terrestrial photograph of the study area. Nevertheless, 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 treeline 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., 2014). Environmental studies in Africa are increasingly using these historical photographs (e.g. Kull, 2005; Osmaston, 1998; Western, 2010).

Repetition of the old terrestrial photograph and post classification comparison of the historical aerial photographs and recent satellite imagery, indicate that the forest cover severely decreased during the twentieth 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 twentieth century (Gebrehiwot et al., 2013). The second deforestation phase in Lib Amba Mt., 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.

A potential 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 km^{-2} for the Ethiopian highlands (Nyssen et al., 2009b). In Ethiopia, 85% of the population and 75% of the livestock lives in the highlands (above 1500 m), which account for only 43% of the Ethiopian territory (Amsalu and de Graaff, 2006; Woldemariam, 1988).

Due to this growing anthropogenic pressure in combination with protection of the afro-alpine forest, the afromontane forest cover severely reduced between 1982 and 2010. At present the afromontane forest remains only in a few patches. This indicates that land management decisions have an important impact. But 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 treeline elevation significantly increased by 7-15 vertical meters (95% CI) between 1965 and 2010. But 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 treeline shift is thus clearly less than in the Sub-Arctic (70-90 m in the last century; (Kullman and 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 treeline 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 treeline change is the result of climate change or land management changes? The land management hypothesis would be in agreement with Chapter 2. This study indicates that treelines have not risen to higher altitudes in the tropical African highlands due to high anthropo-zoogenic pressure, which caused stabilization and even recession of the treelines below their natural climatic limit. Strong disturbance of the treeline by human interference is also found for the Andes mountains by (Young and 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 treeline dynamics is chosen in a protected area, which in the case of long term protection would mean that the observed treeline shift must be climate change driven. But the forest has only been protected for 10 years and the highest treeline shift occurred on the gentle slopes in the western part of the study area in which the treeline was suppressed to a lower elevation. It is thus likely that treeline 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 treeline in the study area.

5.5 Conclusion

This study revealed that there were two periods of deforestation on the slopes of Lib Amba Mt. 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 afro-alpine forests were protected and the population pressure increased from 77 to 153 inhabitants per km^{-2} and. 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 treeline between 1965 and 2010, which lies between 7 and 15 vertical meters. This increase of the treeline elevation is higher on the gentle slopes. Due to the high anthropo-zoogenic pressure in the study area, the potential effect of climate change on the treeline 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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Chapter 6 Land cover dynamics in the Simen Mountains (Ethiopia), half a century after establishment of the National Park

This chapter is based on:

Jacob, M., Frankl, A., Hurni, H., Lanckriet, S., De Ridder, M., Guyassa, E., Beeckman, H., Nyssen, J. (2015). Land cover dynamics in the Simen Mountains (Ethiopia), half a century after establishment of the National Park. Regional Environmental Change, in review.

Abstract

The Simen Mountains are home to several endangered and endemic wildlife species and provide important ecosystem services. But despite its regional environmental importance, the Simen Mountains have been listed as World Heritage in Danger since 1997. This raised the need for an evaluation of landscape changes in the Simen Mountains. Landscape changes are studied from before the establishment of the Simen Mountains National Park (SMNP) in 1969 using historical terrestrial photographs (1966-2009). Repeat photographs from 2014 were analyzed using an expert rating system with eight correspondents. An increase of forest is observed around Sankaber and Imet Gogo (20-40%). But around Gich, the area covered with dense forest decreased with a rate of -1.41% per decade. There is no significant effect ($p>0.05$) of the boundary of the SMNP on woody vegetation change, because of continued anthropo-zoogenic pressure inside the SMNP. Neither do other bio-physical (elevation) or social factors (distance to scout camps) affect rates of change. However, the density of houses within 2.2 km, as a proxy of population pressure, is able to explain 32% of the spatial distribution of decrease in woody vegetation changes ($p<0.05$). A subset of six repeated photographs, indicate an uplift of the treeline by more than 1 m $year^{-1}$, in areas with low anthropo-zoogenic pressure. This is potentially related with a temperature warming of up to 1.5°C over the past 50 years. Overall, further reduction of anthropo-zoogenic pressure is a key factor for recovery of the afro-alpine vegetation and the interrelated endangered wildlife in the Simen Mountains.

Keywords: Vegetation change, Treeline dynamics, Anthropo-zoogenic pressure, Repeat photography

6.1 Introduction

Since the introduction of agriculture, land use has interfered with the natural process of land cover changes (Goudie, 2006; Houghton, 1994). At present, 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 20th 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 sub-alpine 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 Simen highlands from Landsat images of 1984 and 2003 and indicated an increase of the *Erica* forest and a decrease of 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. Improved insight in 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 vegetation of the Ethiopian highlands provides a habitat for several endangered endemic species such as the famous and severely endangered Ethiopian wolf (*Canis simensis*) and Walia ibex (*Capra walie*) (Marino, 2003). Moreover, the afro-alpine vegetation and especially the high altitude forests are also important as a hygric buffer, enhancing ground water availability in the mountain and the surrounding lowlands (Markart et al., 2007; Miehe and Miehe, 1994). 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 is proven 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 Simen 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* forest in the Simen

Mountains is potentially responsive to climate warming (Holtmeier and Broll, 2005). Consequently, this vegetation belt can be studied to achieve understanding of potential dynamics (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 of increasing stand fragmentation and stuntedness, which is called a treeline ecotone (Körner and Paulsen, 2004). The response of the treeline ecotone to present climate change in the tropics and in the southern hemisphere is scarcely investigated comparatively to treeline dynamics at higher northern latitudes (Holtmeier and Broll, 2007). In Chapter 2 it was indicated that treeline dynamics in the African tropical highlands are, in general, limited below their climatic limit due to high anthropo-zoogenic 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 Simen Mountains using repeat photographs (1966-2014) and to understand the drivers of these changes.

6.2 Materials and methods

6.2.1 Study area

The Simen massif (13°14’N, 38°21’E) is home to the highest peak of Ethiopia, the Ras Dejen Mt (4540 m) (Figure 6.1). The massif is a remnant of a major Oligo-Miocene shield volcano, deeply eroded by the Tekeze River and its tributaries (Kieffer et al., 2004). At present, the Tekeze and its tributaries form an arc, which practically encircles the massif. The high Simen Mountains form the most northern limit of glaciation in East Africa during the LGM (Hendrickx et al., 2015; Hurni, 1981). The mountain climate of the Simen contrasts with the semi-arid surroundings. It 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). The diurnal temperature gradient is high with a mean daily temperature variation of 9.0°C (Hurni and Stähli, 1982). Rainfall in the Simen Mts. 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 Simen Mts., associated with the 1000 m high escarpment. With elevation, there are two rainfall maxima, the first at 1500 m and the second at 3500 m (Hurni and Stähli, 1982). At the end of the raining season, in the period September-October, clear mornings are frequently followed by a strong build-up of fog and cause heavy rain and hailstorms at night (Hurni and Stähli, 1982). Snow can be observed in the northern hemisphere winter, though it is then the dry season

(December-January). Hurni (1988) characterized the climate into two categories, the upper (above 3500 m a.s.l.) and the lower (1500-3200 m a.s.l.) climate types. The upper mountain climate is characterized by northerly winds all around the year, an increase in cloudiness with altitude, an annual rainfall maximum near the timberline (on average 1500 mm) and frequent hailstorms which are highly erosive (Hurni and Stähli, 1982). A steep gradient separates the mountain climate from dry and hot conditions at the foot zone of the mountain.

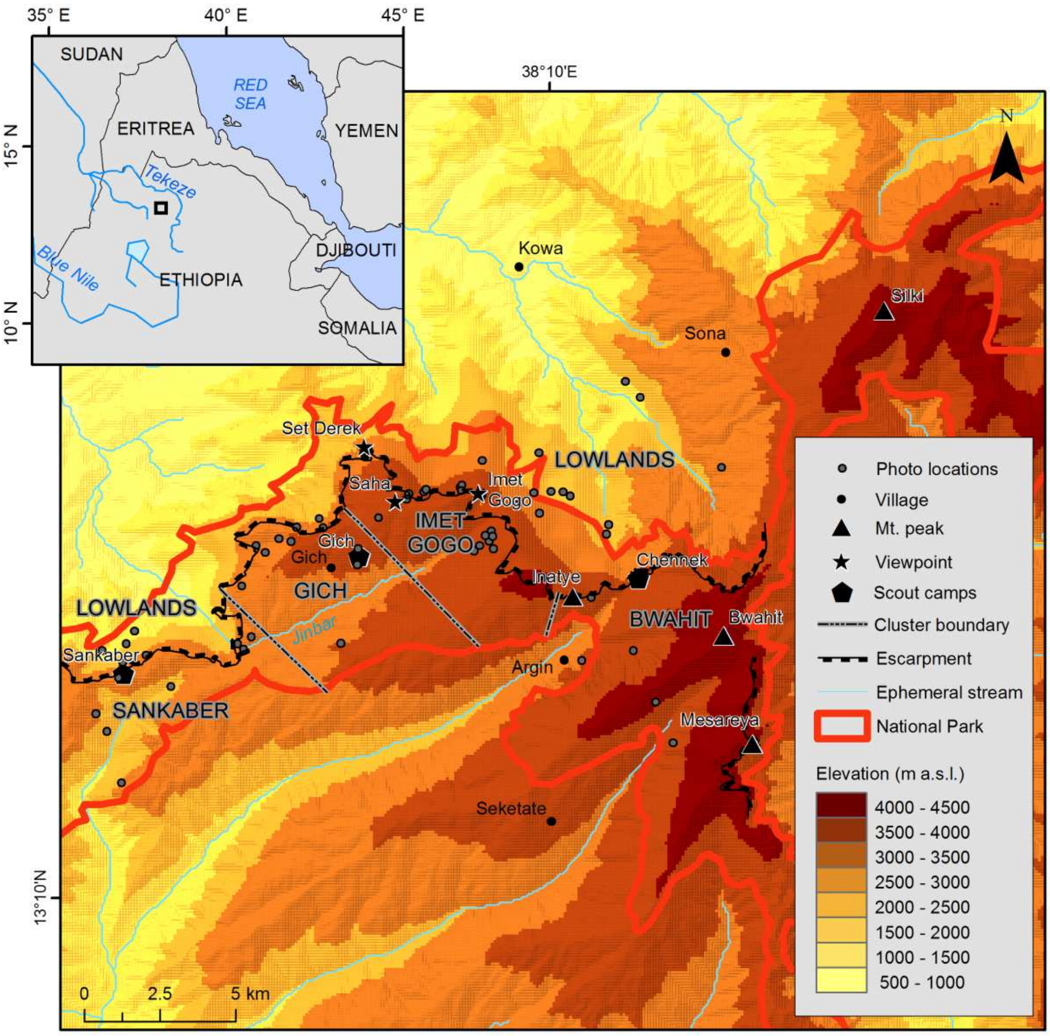

Figure 6.1 Location of the study area with indication of the approximate cluster boundaries; the boundary of the lowlands is formed by the northern escarpment. In the south the boundary is less sharp.

The Simen Mountains National Park (SMNP) form a hotspot in biodiversity, due to their altitudinal and climatic diversity, and are listed as World Heritage since 1978 (Debonnet et al., 2006). The vegetation in the Simen Mts. can be divided in three distinct belts. Between 2000 m and up to 3500 m NE and 3300 m SE the evergreen afromontane 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. c*uspidate* at the drier south-southeast facing slopes. *Juniperus procera* is less common in the Simen Mts (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). The afro-alpine zone contains 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 Simen Mountains are home to several threatened and endemic species. There are more than 20 large mammal species in the Simen Mountains, of which two endangered endemic flagship species: the Walia ibex (*Capra walie*) and the Ethiopian wolf (*Canis simensis*) (Debonnet et al., 2006). There are also more than 130 bird species of which 16 endemic. Many species are endangered due to habitat fragmentation and destruction caused by human impact (Alemayehu et al., 2011; Yihune et al., 2009).

The SMNP was created in 1969, a period when 80% of the park was subjected to human use through livestock grazing, cultivation and human settlements (Debonnet et al., 2006). Population growth forced people to settle and cultivate higher and steeper areas, even marginal lands up to 3800 m a.s.l. are used as cultivation land (Keiner, 2000). The stocking density in the SMNP is also high (up to 55 TLU/ km² in Gich) which affects the afro-alpine grasslands at higher elevations through home-range herding (Keiner, 2000). 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).

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. In 2009 the United Nations Educational, Scientific and Cultural Organization (UNESCO) and International Union for Conservation of Nature (IUCN) initiated a joint mission to assess the state of the SMNP and to guide the park towards a state that would justify its removal from the World Heritages in danger (Debonnet et al., 2006).

6.2.2 Repeat photography

For this study, 98 historical photographs of the Simen Mountains were collected dating back between the 1960s and 2009 (Table 6.1). The photographs were originally taken by Bernhard Nievergelt, Larry Workman, Hans Hurni and Jan Nyssen during various expeditions in the Simen Mountains. The photographs were selected because they give a unique representation of historical vegetation cover on the slopes of the Simen 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 perpendicular axes crossing 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 was used as reference to slightly rotate, rescale and crop the repeated photographs (Frankl et al., 2011).

Table 6.1 Historical photographs used in analysis (n=98)

Year	*Authors*	*Photographs*
1966-1968	Bernhard Nievergelt (Nievergelt et al., 1998)	6
1971-1978	Bernhard Nievergelt (Nievergelt et al., 1998)	5
	Larry Workman (private collection)	13
	Hans Hurni (Centre for Development and Environment, University of Bern)	10
1980-1983	Bernhard Nievergelt (Nievergelt et al., 1998)	5
	Hans Hurni (Centre for Development and Environment, University of Bern)	19
1993-1999	Bernhard Nievergelt (Nievergelt et al., 1998)	9
	Hans Hurni (Centre for Development and Environment, University of Bern)	25
2009	Jan Nyssen (Department of Geography, Ghent University)	6

6.2.3 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. To avoid bias, uninterpretable areas due to foreground errors, shadows or obstructions were masked on the photographs. 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 81 photo-pair interpretations. The experts estimated the land cover distribution as a percentage of the complete scenery (Figure 6.2) (Nyssen et al. 2014b). Based on field experience, nine major land cover classes were determined:

- Areas covered by forest. Subdivided between (i) open forest if the wooded area has less than 50 percent canopy cover and (ii) dense forest if the canopy cover is greater than 50 percent.
- Shrubland: areas dominated by shrubs, generally growing closely to the ground (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 people (i.e. roads, campsites, houses).

Figure 6.2 A repetition of the 1973 photograph by Larry Workman looking towards Sankaber camp. The truncated mean for the land cover class percentages of the 1973 photograph are 7% open forest, 4% shrubland, 72% grassland and 17% rock outcrop. While, for the 2014 photograph these land cover percentages are 19% open forest, 19% shrubland, 51% grassland and 11% rock outcrop. The photograph is masked to differentiate between different major topographic entities.

The procedure of Nyssen et al. (2014b) was 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, i.e. the truncated mean. 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 Simen mountains.

6.2.4 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 Simen Mountains. To understand temporal changes in woody vegetation, the observations were divided in two periods 1966-1978 and 1980-2009 in comparison to the current situation (2014). The changes are mapped for an area 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 escarpment forms a structural boundary in the landscape and is 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 Simen Mountains, four potential explanatory factors were measured for every observation: (i) inside or outside the National Park boundary, (ii) elevation, (iii) population density and (iv) 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.

6.2.5 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. Subsequently, 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.

6.3 Results

6.3.1 Vegetation cover change

In the highlands, grassland is the most important land cover class with between 33 and 67% of the total vegetation cover. This class is, however, decreasing around Sankaber (-4%) and Imet Gogo (-9%), where grassland is removed in favor of woody vegetation. Beside grassland, also rock outcrop is decreasing in most sites. On the other hand, cropland increased in the lowlands (+1%) and also in the highlands in Gich (+2%) and around Bwahit (+2%) area (Figure 6.3).

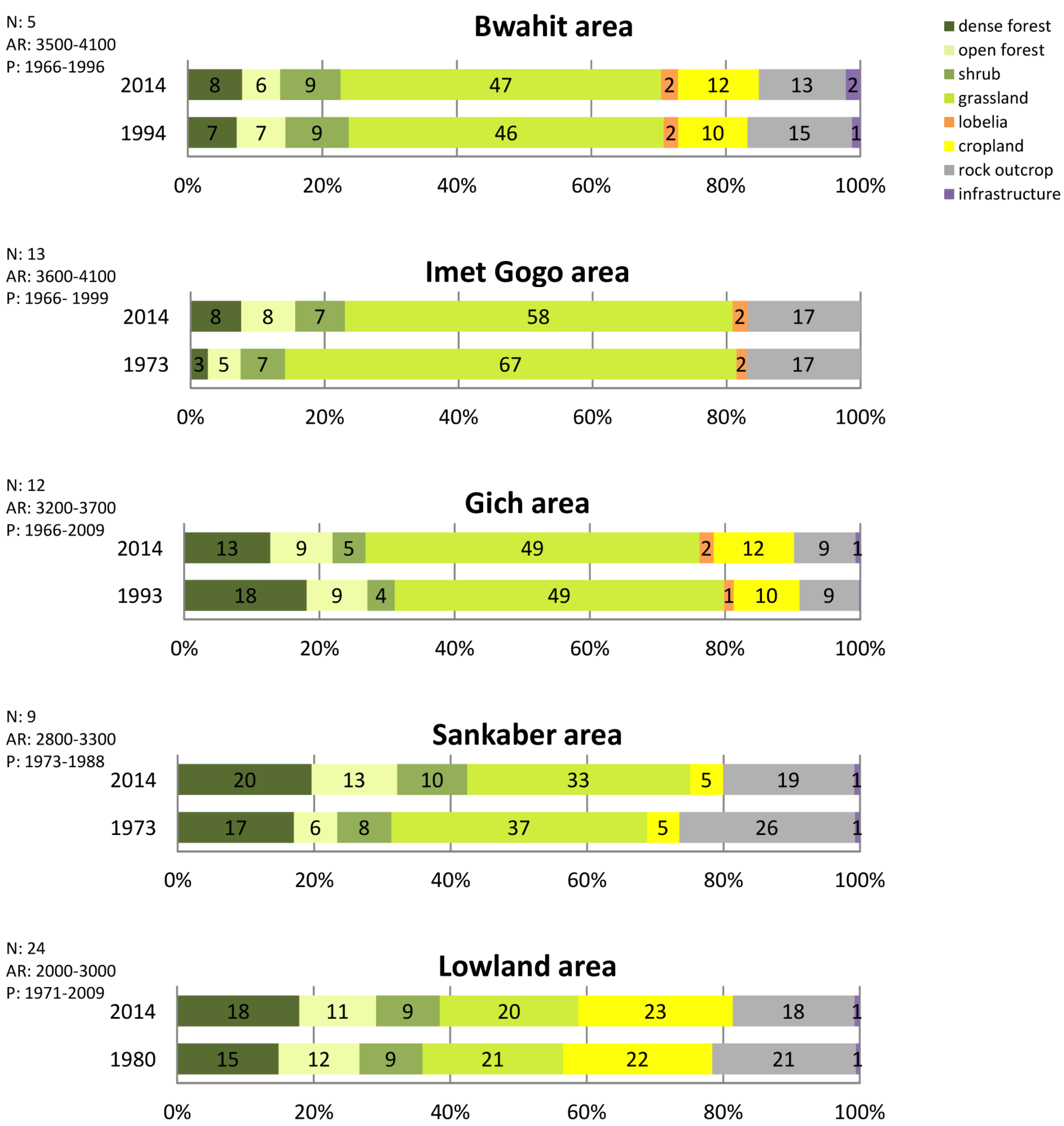

Figure 6.3 Average land cover percentage for the past and current landscape in the Simen Mountains as derived from repeat photographs for (a) Bwahit area, (b) Imet Gogo area, (c) Gich area, (d) Sankaber area and (e) the lowland areas north of the escarpment. With N: the number of photo locations, AR: the altitudinal range of the pictured landscapes, and P: the period of the photographs (the median year is used in front of the historical cumulative histogram).

Decadal changes (Figure 6.4) indicate an increase of the dense forest in all areas except in Gich. In Gich the dense forest decreased with a rate of -1.41% of the total area per decade and also the area covered by grasslands is decreasing, while cropland is the most important growing class (+0.98% per decade). Around Bwahit there is also a considerable increase of the area covered by cropland (+0.52% per decade). Although dense forest increased around Bwahit, open forest and bushland decreased here. The cropland area also increased in the lowlands (+0.24% per decade). However, the most important increasing class in the lowlands is dense forest with +1.37% 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 of dense forest is especially high in Imet Gogo (+1.40 % per decade).

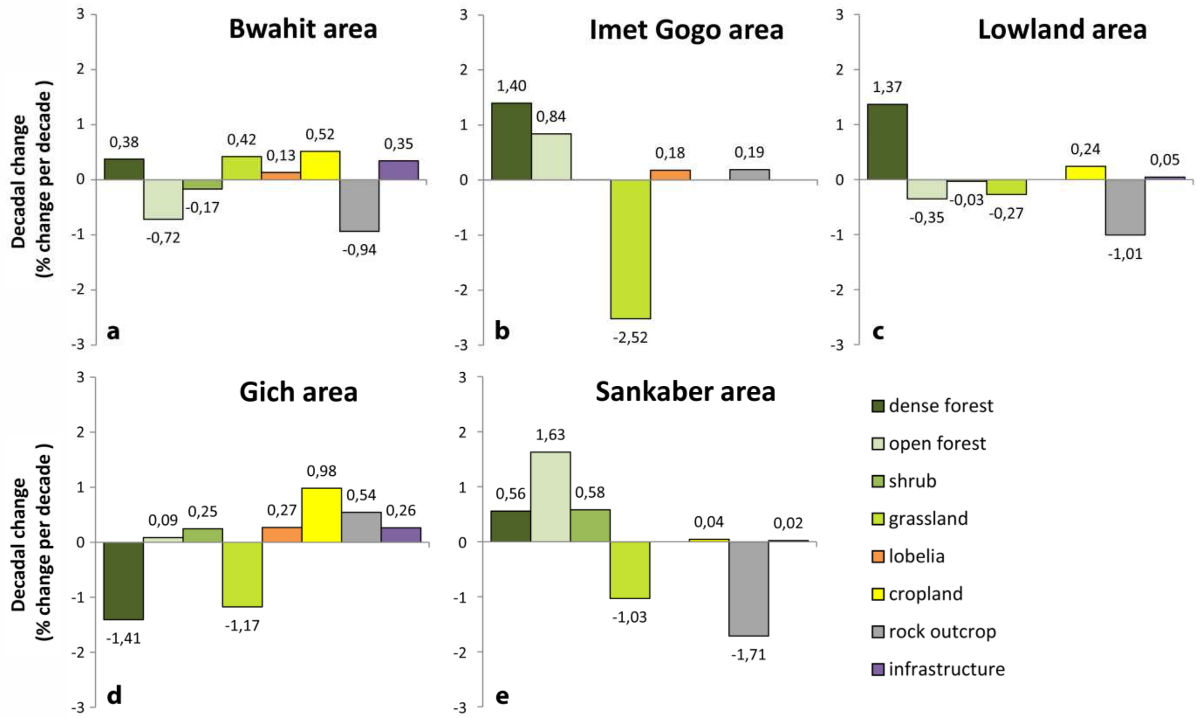

Figure 6.4 Decadal land cover changes in the Simen Mountains as derived from repeat photographs for (a) Bwahit area, (b) Imet Gogo area, (c) Lowland areas north of the escarpment, (d) Gich area and (e) Sankaber area.

6.3.2 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 ($p>0.05$) (Figure 6.5A). The boundary of the National Park is not significantly explanatory for changes to woody vegetation in the Simen Mountains. This absence of impact of the National Park is also visible on the woody vegetation cover change map for the period after 1980. Changes in the woody vegetation after 1980 are limited throughout the study area, the majority of observations showing a small increase. The observed changes since the period before 1980 are more diverse. Around Gich the woody vegetation clearly decreased (-30 to -10%), while around Sankaber and Imet Gogo there is a remarkable increase of the woody vegetation (20-40%). In Figure 6.6, 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 (Figure 6.7).

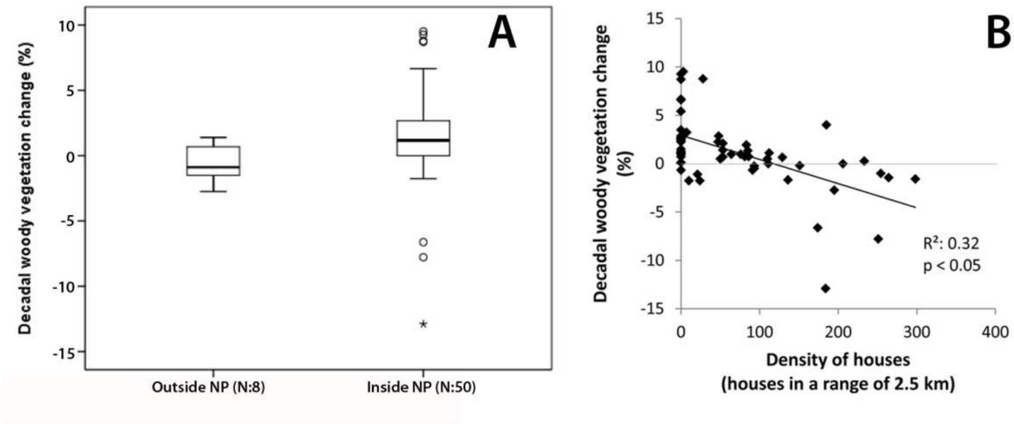

Figure 6.5 Decadal woody vegetation change over the full period (1966-2009) (a) inside and outside the National Park, and (b) in relation to the density of houses per photographed scene as proxy for population pressure.

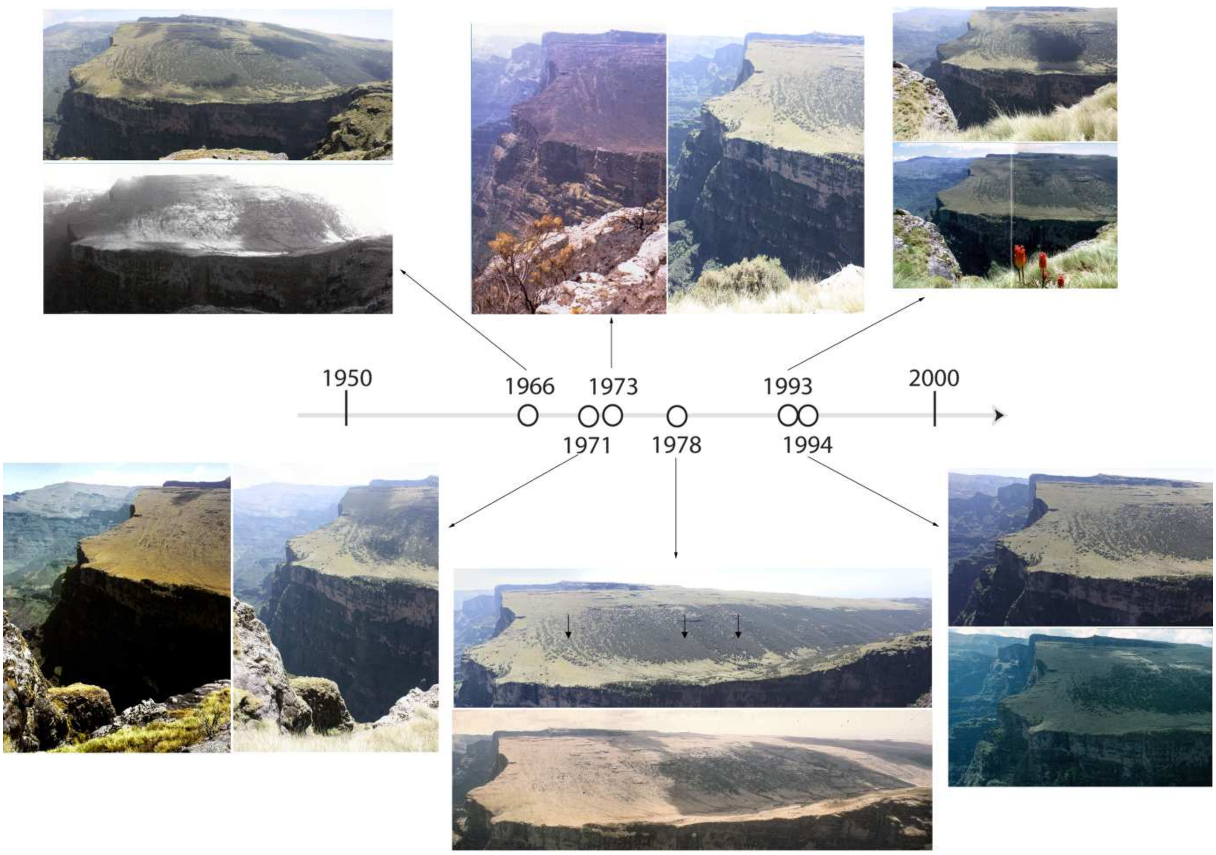

Figure 6.6 Repeat photographs of 1966-1994 and 2014 illustrating vegetation cover change in the upper Jinbar valley (part of the Imet Gogo cluster). Interpretations have to take into account that there has been a forest fire in this valley in the early 1970s (Hurni, personal communication; Nievergelt et al. 1998). Notice also the

preferential growth of *Erica* on the small ridges in 1978 (see arrows on the 1978 photograph), what corresponds with the findings in Chapter 4 and the improved stability of the middle gully at present. 1966, 1971 and 1994 photographs by Bernhard Nievergelt, 1973 photograph by Larry Workman and 1978 and 1993 photographs by Hans Hurni.

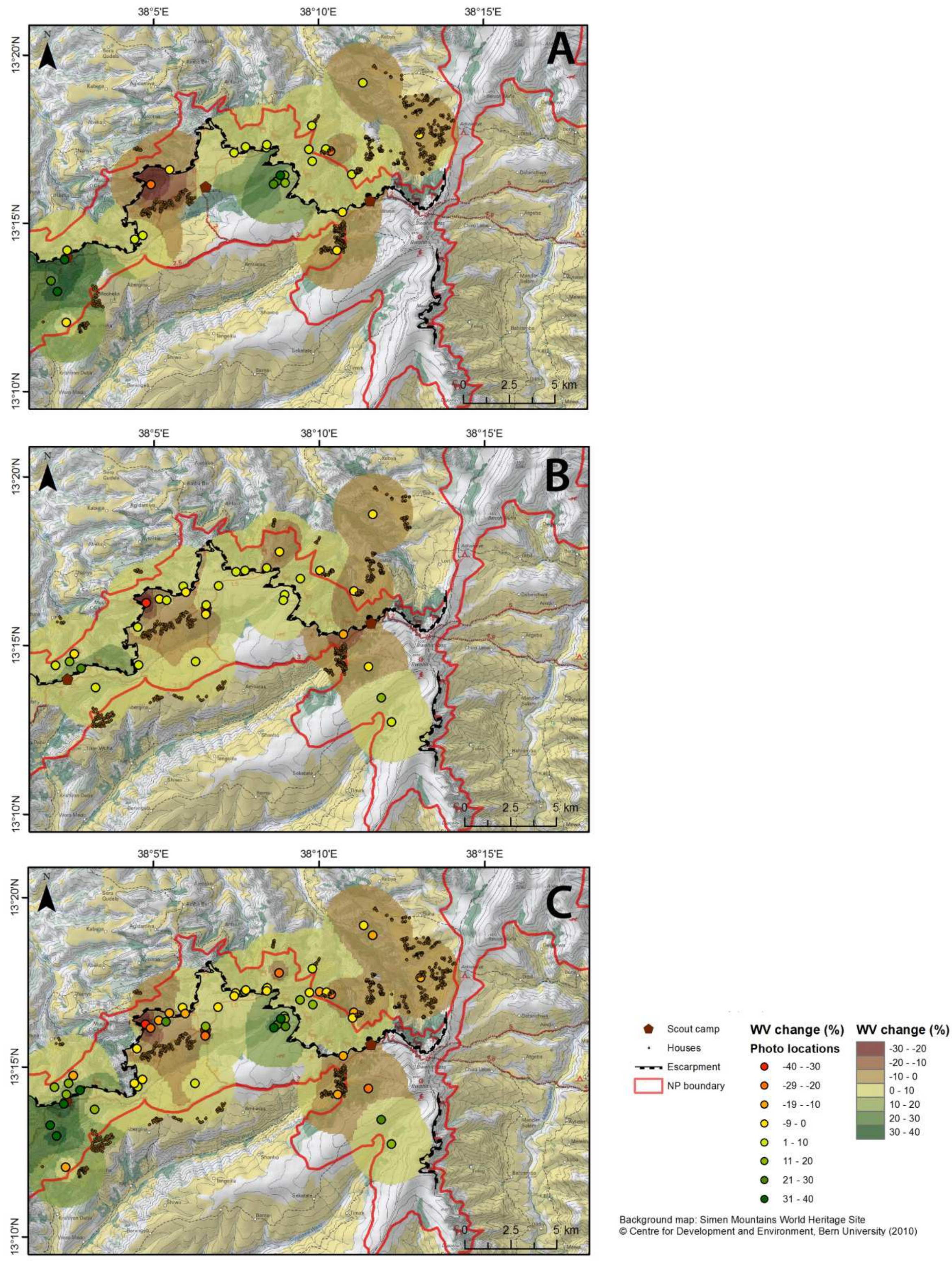

Figure 6.7 Woody Vegetation (WV) cover change maps for 2014, as compared to (a) 1966-1978, (b) 1980-2009 and (c) 1966-2009.

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 neighborhood of 2.2 km is used as a proxy for the population pressure and explains 32% of the observed spatial variation for the total period (Figure 6.5B).

6.3.3 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 6.2). 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 (Figure 6.8) and Argin valley, the physiognomic treeline rose respectively with 2.5 and 3.1 m year^{-1} during the last 20 years (since 1994).

Figure 6.8 Treeline dynamics in Seketate valley as derived from repeat photographs in the Simen Mountains (1994-2014). The 30% forest cover isoline is indicated in yellow. The upper 1994 photograph is taken by Hans Hurni.

Table 6.2 Dynamics of the upper and physiognomic treeline derived from repeat photographs of the Simen Mountains.

	Slope	*Peak (m asl)*	*Interval*	*Years*	*Upper individuals (m asl)*		*shift (m)*	*Physiognomic treeline (m asl)*		*Shift (m)*	*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

6.4 Discussion

6.4.1 Land use and National Park management

The finding that there is no significant effect of the National Park boundary on woody vegetation changes is remarkable. This can be partly explained by early colonization of marginal lands in the lowlands outside the NP, which leaves limited space for further expansion of the cultivation land. At present, even the reverse is observed: marginal cultivation land on steep slopes is abandoned in the lowlands (Figure 6.9). On the other hand, the continuing anthropo-zoogenic pressure in the National Park is responsible for the lack of an effect from the National Park boundary. The area covered by grassland is relatively stable; it is only decreasing in favor of forests in Sankaber and in Imet Gogo. Unfortunately, this study gives no insight in the condition of the grassland. Nevertheless, the condition of the grass is of key concern for the ecosystem. The Simen Mountain National Park (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 towards 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 (*Capra walie*) population was heavily poached in that period, the natural resources of the park were not 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). The direct proximity to the scout camp of Sankaber is a potential explanatory variable for this observed increase in woody vegetation. But overall we cannot conclude that the location of the three scout camps have a significant effect on woody vegetation changes. Moreover, the areas in the surroundings of Gich and Chennek camp show a decrease in the woody vegetation. This is the result of the strong influence of population in Gich and Argin. Strong human pressure on the environment is also observed in neighboring 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 anthropo-zoogenic disturbances cause an increase of landslides (Mugagga et al., 2012).

Figure 6.9 Looking down from Imet Gogo to Truwata village. In 1974 (photo by Hans Hurni) fire was used for deforestation for the extension of cultivated land, while in 2014 the cultivation land on the steep marginal slopes has been abandoned (white arrows).

In contrast to the findings in this study, Wondie et al. (2011) observed a decrease of cropland and an increase of 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. However, there is no evidence for the existence of cropland in this area on the historical photograph of Larry Workman from 1973 (Figure 6.2). On average, an overall increase of dense forest was also found in this study. But, more important are the spatial patterns of woody vegetation change, which indicate the negative effects of continued anthropo-zoogenic pressure.

The ongoing deterioration of the natural environment at the village of Gich is clearly indicated in this study. This is a well-known concern for sustainable management of the SMNP. Previously in 1979, seven villages inside the National Park were destroyed (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 villages, 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 with almost 10,000 ha and the population within the National Park was reduced with 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 towards removal from the Danger list. Caution is needed since the park resources are not only used by people inside the national park, also communities living in the vicinity use these resources.

6.4.2 Upwards shift of the *Erica* treeline

An upward movement of the upper forest, in areas under decreased influence of anthropo-zoogenic pressure, is observed in the Simen Mountains (Figure 6.10). The observed shift near to Seketate and Argin is remarkable taking into account 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 Simen 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* forests by about 150 m.

Such evidences of a risen treeline elevation in areas under low anthropo-zoogenic pressure provide proof for a potential climatic effect (Hurni, 2005). The observed treeline uplift in the study corresponds, according to the altitudinal temperature lapse rate for East Africa of 0.6°C per 100 m (Peyron et al., 2000), with a temperature effect between 0.5 and 1.5 °C since 1966. This increase of the air temperature 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.

Figure 6.10 Repeat photographs of the Simen Mountains, (left) Kedadit Mt. (Imet Gogo cluster) showing the appearance of *Erica* bushes (red arrows) in the recent photograph where no *Erica* is visible on the 1973 photograph (by Larry

Workman). (right) Inatye mountain, the treeline elevation shifted 245 m upwards between 1966 (photograph by Bernhard Nievergelt) and 2014 (white arrows), from 3631 to 3879 m.

6.5 Conclusion

The Simen Mountains provide a habitat for several endangered endemic species and provide important ecosystem services to the environment. However, since 1997, the Simen Mountains are listed as World Heritage in danger. Landscape changes derived from repeat photographs (from the period 1966-2009) indicate that the natural landscape is to date (2014) still under pressure by anthropo-zoogenic impacts. This is especially the case around the villages of Gich and Argin. On the other hand, this study also indicates a positive evolution of increased woody vegetation around Sankaber and Imet Gogo. Moreover, in locations isolated from anthropo-zoogenic pressure an increase of the upper treeline is observed, which is potentially related with a climate warming up to 1.5°C over the last 50 years. Continued reduction of the anthropo-zoogenic pressure is thus a key element for a recovery of the afro-alpine vegetation and associated wildlife habitat.

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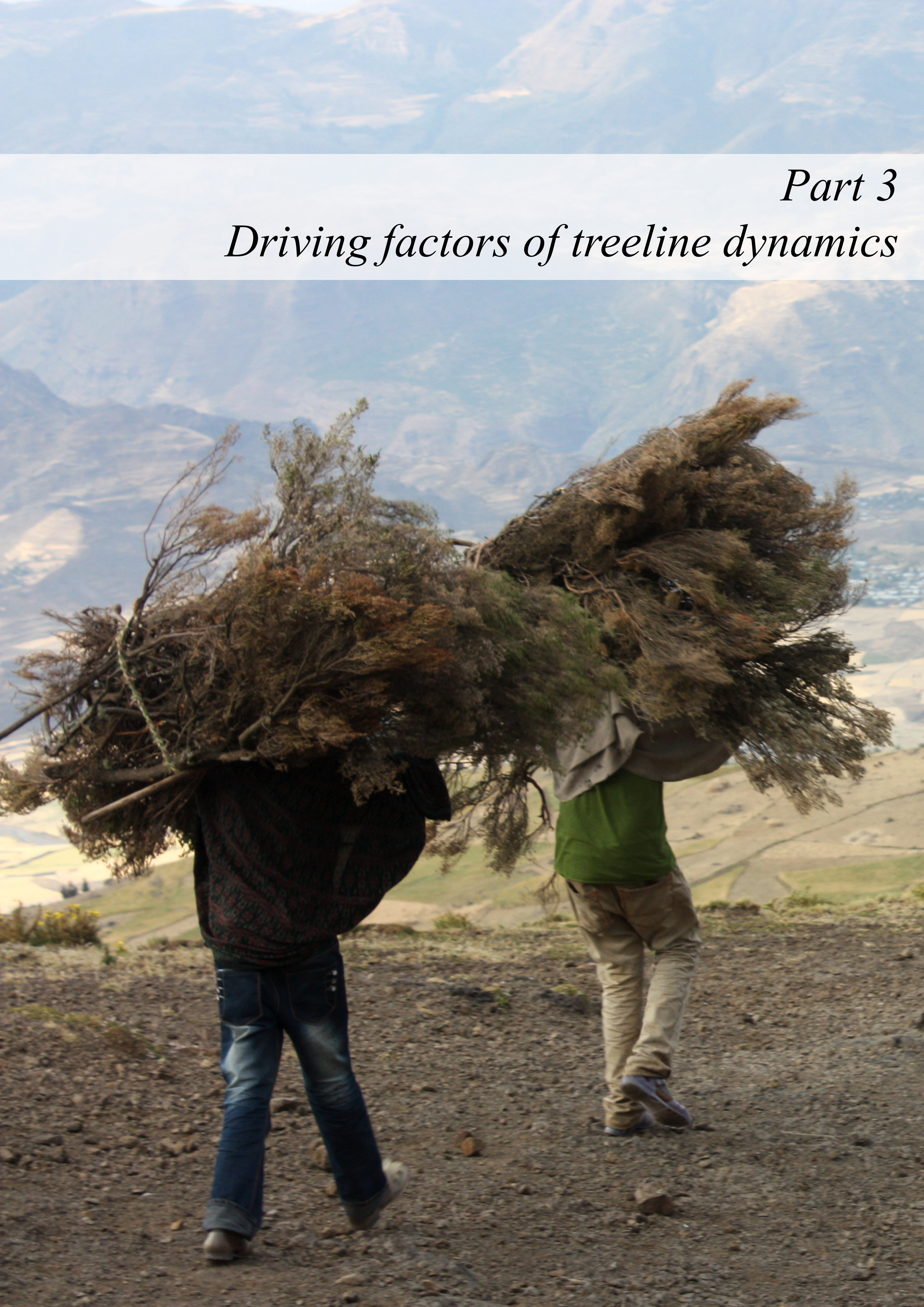
Part 3
Driving factors of treeline dynamics



The photograph on the back of this page is taken at the northern slope of Ferrah Amba Mountain on 17 November 2014. The two boys on the photograph are carrying dried *Erica* branches to their house. The branches are used as firewood for cooking.

Chapter 7 Assessing spatio-temporal rainfall variability in a tropical mountain area (Ethiopia) using NOAAs Rainfall Estimates

This chapter is based on:

Jacob, M., Frankl, A., Mitiku, H., Zwertvaegher, A., Nyssen, J. (2013). Assessing spatiotemporal rainfall variability in a tropical mountain area (Ethiopia) using NOAAs Rainfall Estimates. International Journal of Remote Sensing, 34 (23), 8305-8321.

Abstract

Seasonal and interannual variation in rainfall can cause massive economic loss for farmers and pastoralists, not only because of deficient total rainfall amounts but also because of long dry spells within the rain season. The semi-arid to subhumid mountain climate of the North Ethiopian highlands is especially vulnerable to rainfall anomalies. In this paper, spatio-temporal rainfall patterns are analyzed on a regional scale in the North Ethiopian highlands using satellite-derived Rainfall Estimates (RFE). To counter the weak correlation between the RFEs and the Meteorological Station (MS) rainfall data in the dry season, only the rain season rainfall from March till September is used, responsible for *ca.* 91% of the annual rainfall. Validation analysis demonstrates that the RFEs are well correlated with the MS rainfall data, i.e. 85% for RFE 1.0 (1996-2000) and 80% for RFE 2.0 (2001-2006). However discrepancies indicate that RFEs generally underestimate MS rainfall and the scatter around the trendlines indicates that the estimation by RFEs can be in gross error. A local calibration of RFE with rain gauge information is validated as a technique to improve the RFEs for a regional mountainous study area. Slope gradient, slope aspect and elevation have no added value for the calibration of the RFEs. The estimation of monthly rainfall using this calibration model improved on average by 8%. Based upon the calibration model, annual rainfall maps and an average isohyet map for the period 1996-2006 were constructed. The maps show a general northeast-southwest gradient of increasing rainfall in the study area and a sharp east-west gradient in its northern part. Slope gradient, slope aspect, elevation, easting and northing were evaluated as explanatory factors for the spatial variability of annual rainfall in a stepwise multiple regression with the calibrated average of RFE 1.0 as dependent variable. Easting and northing are the only significant contributing variables (R^2: 0.86), of which easting has proven to be the most important factor (R^2: 0.72). The scatter around the individual trendlines of easting and northing corresponds to an increase of rainfall variability in the drier regions. The improved estimation of spatio-temporal rainfall variability in a mountainous region by RFEs is, although the remaining underestimation of rainfall in the southern part of the study area, valuable as input to a wide range of scientific models.

Keywords: RFE, North Ethiopian highlands, Calibration, Rainfall patterns

7.1 Introduction

In drought years, millions of Ethiopians are dependent on assistance (Segele and Lamb, 2005), not only because of deficient total rainfall amounts but also because of long dry spells within the rain season (Seleshi and Camberlin, 2005). The northern Tigray region is the driest region in the semi-arid to subhumid mountain climate zone of the North Ethiopian highlands (Nyssen et al., 2005). Seasonal and inter-annual variation in rainfall can cause massive economic loss for abundant poor rural farmers (dependent on rain-fed agriculture) and pastoralists (Shanko and Camberlin, 1998). The severe impact of successive dry years has been demonstrated repeatedly in Ethiopia, e.g. the droughts of 1973-1974 and 1982-1985 claiming the lives of several hundred thousands of people (Tilahun, 2006a). Rainfall is not only of main importance for agriculture, but is also a driving force of water erosion processes (Nyssen et al., 2005). Nevertheless climatological studies have been neglected for a long time in the arid and semi-arid tropical regions (Tilahun, 2006b). Recently characterization and variability of rainfall in Ethiopia are more widely studied (Cheung et al., 2008; Conway, 2000; Nyssen et al., 2005; Segele and Lamb, 2005; Seleshi and Camberlin, 2005; Seleshi and Zanke, 2004; Tilahun, 2006a, 2006b).

The aim of this paper is to analyze rainfall patterns not only in time, but also spatially for the period 1996-2006. Analyzing spatiotemporal rainfall patterns is rendered possible by use of satellite-derived Rainfall Estimates (RFE) and through the establishment of a relation between rainfall measured in Meteorological Stations (MS) and RFE. The advantage of this method is that “satellite rainfall estimates fill in gaps in station observations” (Verdin et al., 2005). Besides National Oceanic and Atmospheric Administration Climate Prediction Center (NOAA-CPC) RFE, there are other satellite rainfall products with a high spatial and temporal resolution such as ARC, 1DD, 3B42, CMORPH, TAMSAT. Dinku et al. (2007) validated these algorithms for the complex topography of Ethiopia and concluded that CMORPH and TAMSAT performed the best. Nevertheless RFEs are used in this regional study, because of the particularly high spatial resolution (0.1°) and the opportunity to use historical data starting from 1996. The choice for the RFE algorithm is also important given the widespread use within the Famine Early Warning System (FEWS) of USAID, as a tool for climate monitoring over Africa (FEWS NET, 2010a). Shrestha et al. (2008) have used RFEs to develop a hydrological modeling system of the Bagmati River Basin of Nepal. Senay and Verdin (2003) used the RFE derived Water Requirements Satisfaction Index (WRSI) to calculate seasonal crop water balances.

The validation of RFE in Africa is insufficient and mainly occurred in the west and south of the continent (Dinku et al., 2007). Dinku et al. (2007) therefore made a validation study over the east African complex topography which indicates that the estimations by

RFE 2.0 version performs less well than the RFE 1.0 version. Subsequently, Dinku et al. (2010) investigated the effect of mountainous and arid climates on RFEs in East Africa. The RFEs exhibit a moderate underestimation of rainfall over mountainous regions and high overestimation of rainfall over dry regions (Dinku et al., 2010).

In this paper the possibilities of using RFEs for spatio-temporal rainfall analysis on a regional scale in a mountainous area is studied. Therefore the RFEs are validated and calibrated for the regional study area using MS rainfall data.

7.1.1 Climatic background

The North Ethiopian highlands are part of the ‘African drylands’ characterized by unreliable seasonal rainfall. Rainfall averages (1996-2006) based upon rainfall data of the meteorological stations (without missing values) indicate that rainfall distribution in the study area follows a unimodal rainfall pattern with an unreliable short rainy season preceding the main rain season (Figure 7.1). Rainfall in the North Ethiopian highlands is the result of two main processes: the dominant process is convective rainfall and orographic rainfall occurs where winds pass topographic obstacles (Daniel, 1977). The mean annual rainfall in the Tigray region varies around 600 mm year^{-1} (Krauer, 1988). The daily rain pattern is dominated by afternoon rains (with 47% of the rainfall from 12 to 18 PM) provoked locally by the convective nature of the rains after morning heating of the earth surface (Krauer, 1988).

Rainfall in the North Ethiopian highlands is mainly dependent on the movement of the Intertropical Convergence Zone (ITCZ) (Goebel and Odenyo, 1984). The ITCZ is situated south of the equator in Eastern Africa during the winter in the northern hemisphere. The climate of North Ethiopia is then dominated by high pressure cells of the eastern Sahara and Arabia. North-east winds are prominent with dry airstreams from the Sahara that result in dry weather, this period is known as the bega season (Figure 7.1) (Seleshi and Zanke, 2004; Westphal, 1975). From March to May the Saharan and Arabian high pressure system weakens and moves north. Over the Red Sea the low pressure area remains and over Sudan a low pressure center develops. During this period onshore east and south-east winds are prominent. Spring rains can occur as a result of the change in pressure cells, this small rain season is known as the azmera season (Figure 7.1). In May the monsoon establishes, associated with the northwards movement of the Intertropical Convergence Zone (ITCZ). Unstable, warm, moist air with eastern wind passes over the Indian Ocean and converges with the stable, continental air and provokes frontal precipitation in the eastern and southern part of Ethiopia (Seleshi and Zanke, 2004; Westphal, 1975). At the end of June the ITCZ is in his most northern position (16 - 12°N) initiating the main rain season from June to September, known as kiremt (Figure 7.1) (Cheung et al., 2008). Kiremt rain is responsible for 65 to 95 % of the total annual amount of rainfall (Segele and Lamb, 2005). According to Westphal (1975) the weather during this period is dominated by the monsoon low pressure of India and Pakistan. Winds in the lower troposphere come prominently from the west and these air masses are moist and cool, as they originate from the South Atlantic and absorb vapor passing the equatorial forest, these are the main source of moisture for Ethiopia (Goebel and Odenyo, 1984; Segele and Lamb, 2005; Westphal, 1975).

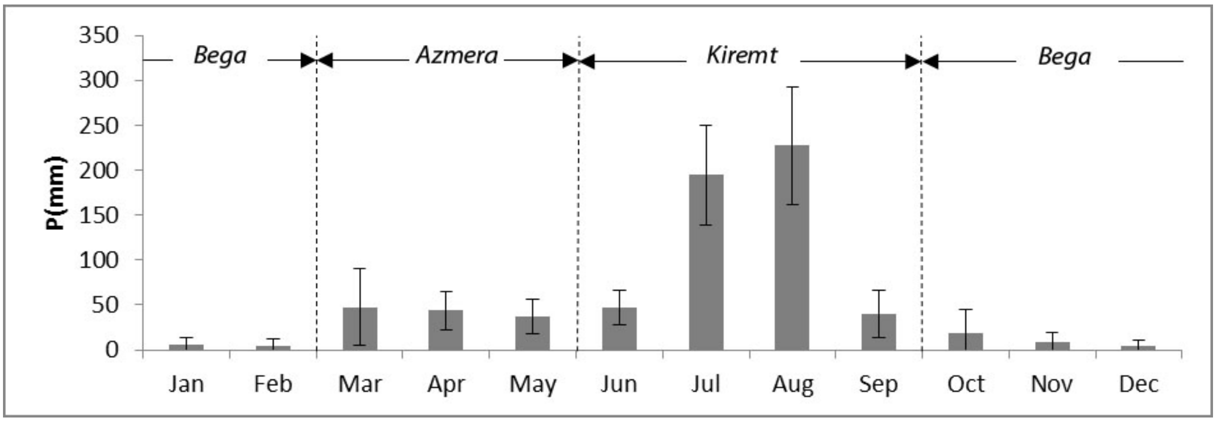


Figure 7.1 Rainfall averages (1996–2006) with standard deviation based on rainfall data of the meteorological stations in the study area (without absent values). The seasonal borders are indicated by dotted lines: the bega (dry) season begins in October and ends at the beginning of March.

In the rain season the dominant western wind in the lower troposphere provokes more rainfall on western and southern slopes (Nyssen et al., 2004). As a result the North Ethiopian highlands intercept most of the monsoonal rainfall in the region, provoking a strong moisture deficit at the Rift Valley (Legesse et al., 2004). Tilahun (2006b) calculated the probabilities of wet and dry periods for Mekelle (regional capital of Tigray). In the period July-August the probability of a dry period of 2 days is very low (ca. 2%). At the same period the maximum probability for a wet day occurs, on 9 August with 75%. In contrast, in the period October-February the probability of a dry period of one week is about 90%, rainfall in this period is highly unreliable. A proportion of only 2% of the rain-days is responsible for 40% of the total rainfall (Tilahun, 2006a).

7.2 Materials and method

7.2.1 Study area

The Federal Democratic Republic of Ethiopia is a landlocked state of 1 104 300 km^2 (UN, 2010) in the horn of Africa. The study area (20 800 km^2) covers a north-south transect strip across the eastern part of Tigray, the most northern region of Ethiopia (Figure 7.2). The study area is delimited to reflect the regional variability in environmental characteristics, i.e. variations in climate, topography and soil. The study area is situated on the western shoulder of the Rift Valley between 12°40’ and 14°23’N and between 38°55’ and 39°49’E with the towns of Adigrat in the northernmost and Maychew in the southernmost position. The elevation of the study area ranges from 1000 to 3939 m a.s.l. (at the Ferrah Amba summit) (Figure 7.2). The relief is characterized by a stepped morphology reflecting the subhorizontal geological structure (Nyssen et al., 2007). Towards the east of the Tigray region, on the border with the Afar region, the altitude lowers rapidly towards the East African Rift valley. This change in topography is the water divide between the westwards drainage towards the hydrological basin of the Tekeze river and that eastwards towards the basin of the East African Rift.

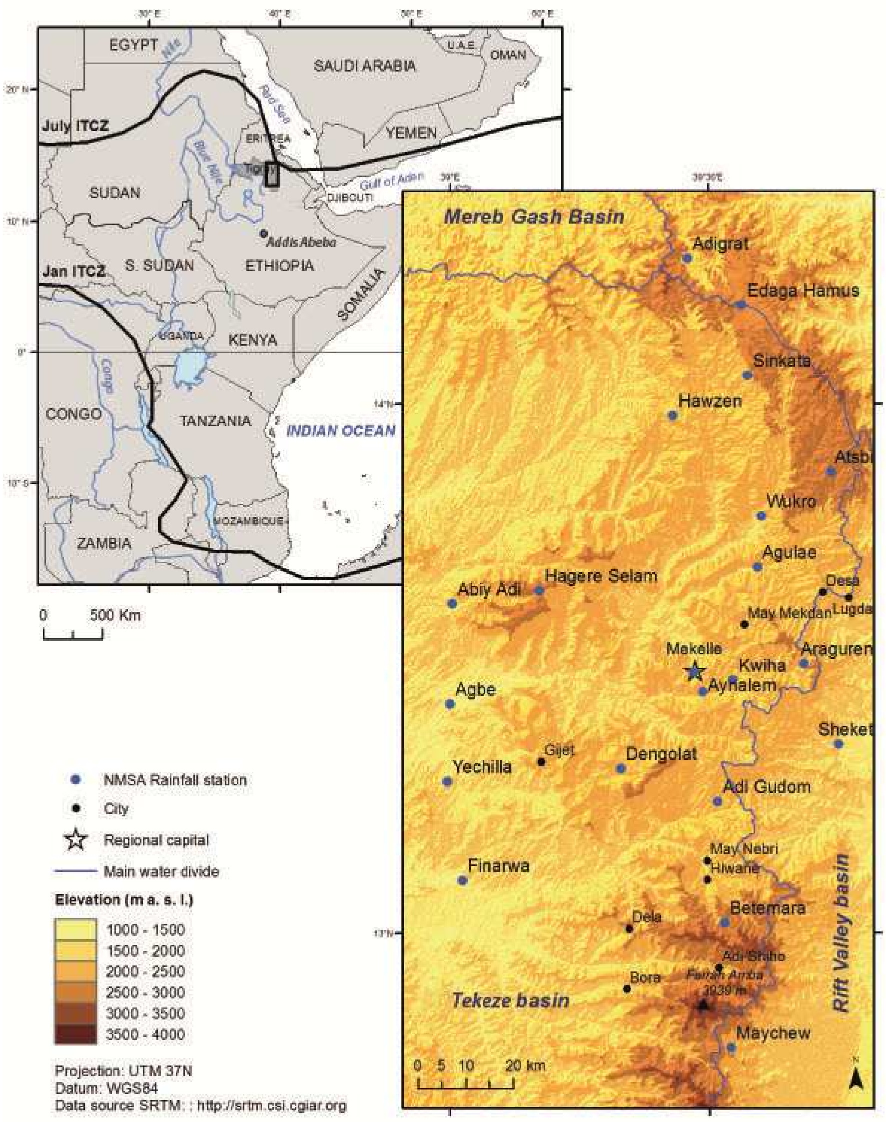


Figure 7.2 Location of the study area in the Horn of Africa, on the western shoulder of the Rift Valley, along a north–south transect across eastern and southern Tigray. Notice the position of the ITCZ in January and July on the regional map.

7.2.2 Meteorological stations

The National Meteorological Agency of Ethiopia (NMA) currently has 61 meteorological stations in Tigray, classified as synoptic, principal, 3rd, and 4th class stations (NMA 2010). The stations are located in urbanized areas, leading to a lack of information within agricultural and scarcely populated areas. In this research a NMA dataset of 21 meteostations from eastern Tigray is used with rainfall data starting from the early 1960s up to 2006 (Figure 7.3). The quality of the data strongly varies between the stations in terms of both timespan and missing records. Four stations (Agulae, Araguren, Betemera and Finarwa) have no data for the research period (1996-2006). The remaining 17 meteorological stations are used for the calculations, this corresponds in theory with a density of 1 station every 1224 km^2 in the study area. But in reality the stations are unevenly distributed, they are mainly located in the north and the center and only limited in the south of the study area.

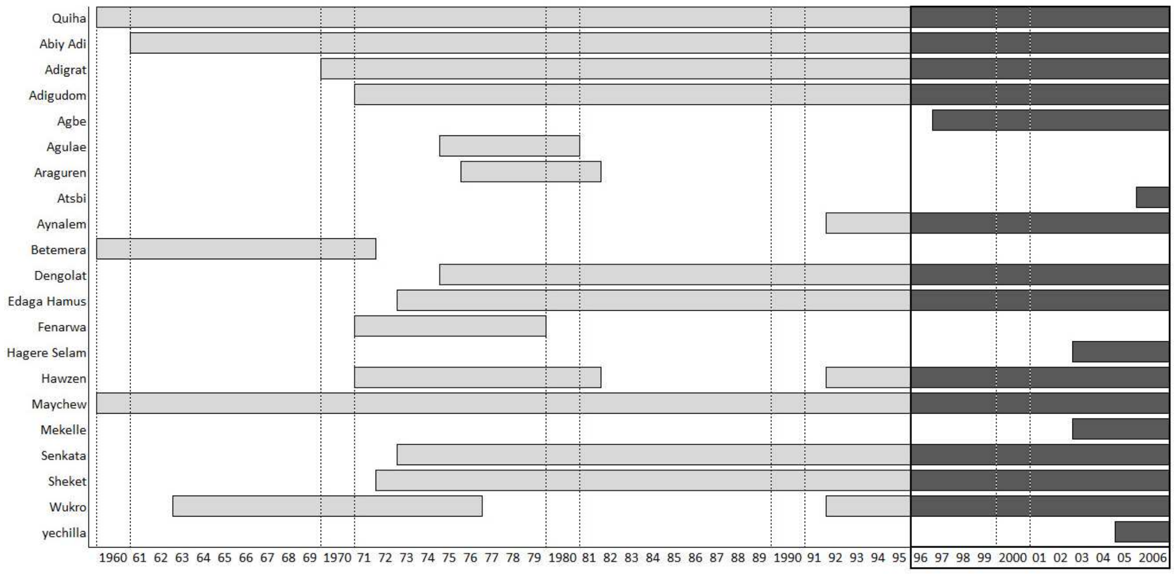


Figure 7.3 Rainfall measurement operation interval of the 21 NMA meteorological stations (1960–2006).

7.2.3 Spatiotemporal rainfall analysis

Data and preprocessing

Satellite derived Rainfall Estimates (RFEs) of North Ethiopia were accessed from the NOAA-CPC on http://www.cpc.ncep.noaa.gov/products/fews/. With a spatial resolution of 8 x 8 km^2, decadal RFE could be downloaded over the period 1996-2006. RFEs of the period 1996-2000 are based on the algorithm developed by Herman et al. (1997). The 1.0 algorithm relates convective precipitation to cold cloud tops observed on Meteosat 7 infrared satellite images and orographic precipitation to warm cloud precipitation due to orographic lifting observed through the integration of surface wind direction, relative humidity and orography. The 1.0 algorithm is enhanced by incorporating rain gauge reports from approximate 1000 stations over Africa. RFEs of the period 2001-2006 are based on the 2.0 algorithm developed by Xie and Arkin (1996). In addition to the version 1.0, RFEs version 2.0 incorporates two rainfall estimation instruments (Special Sensor Microwave/Imager and the Advanced Microwave Sounding Unit). Also in contrast to the 1.0 algorithm, warm cloud precipitation is no longer included in the algorithm.

Daily rainfall of the 17 meteorological station (MS) and decadal data of the RFE were summed to monthly data for the corresponding periods without missing MS data. Assigning MS data to specific RFEs pixels was done in ArcGIS® 9.2 by projecting the location of the rainfall station into the Albers equal area conic projection (Clarke 1866 spheroid) used for the RFEs; with as origin of latitudes 1°, central meridian 20°, first standard parallel -19°, and second standard parallel 21°(FEWS NET, 2010b).

Validation and calibration of the Rainfall Estimates

Rainfall detection capabilities of satellite derived rainfall estimates (RFE) are less accurate over the complex topography of the semi-arid Ethiopian Highlands (Dinku et al., 2010). Therefore they advised to incorporate local rain gauge observations to improve the accuracy of the RFE images. In this paper a local calibration of the RFE images with meteorological stations is verified as a technique to improve the rainfall estimations and study rainfall patterns in a spatio-temporal context.

The statement by Beyene and Meissner (2010) that RFE images are less accurate in measuring rainfall in the dry season (from October to February) is also true in our study (Figure 7.4). Consequently only the rainfall in the azmera and kiremt rain season, which is responsible for an average of 91% of the total yearly rainfall (1996-2006), was used to calibrate the RFE images. Rainfall in the dry season was thus neglected in the calibration model and could not be compensated by an extrapolation of the rain season. Rainfall amounts in the dry and rain season did not correlate significantly (R^2: 0.1391, P: 0.26, 1996-2006).

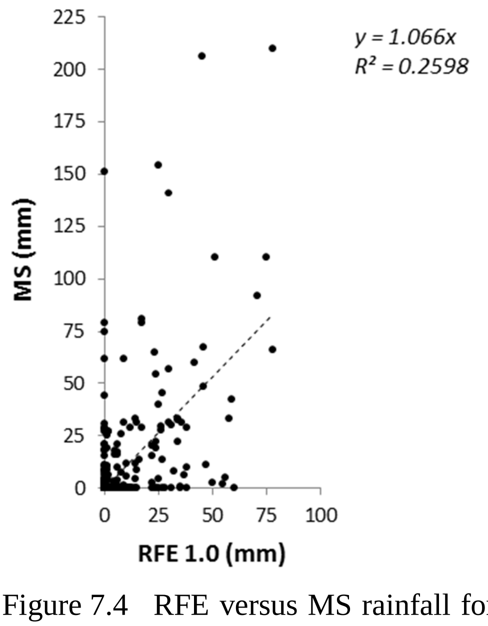


Figure 7.4 RFE versus MS rainfall for the dry season (1996–2000). The correlation between MS and RFE1.0 rainfall values for the dry season (October–February) is low (R2 = 0.26).

In order to assess whether RFEs accurately estimate monthly rainfall, a linear regression analysis was performed in SPSS® 20 with MS as independent variables and RFEs (versions 1.0 and 2.0) as dependent variable (Dinku et al., 2007; Funk and Verdin, 2003). The model was forced through the origin as this zero-zero point is the only point that fits 100% with reality. The advantage of this method is that a bias at the origin of 16 mm for RFE1.0 and 12 mm for RFE2.0 is excluded from the model. The Abiy Adi station was excluded from the analysis as a large discrepancy between MS and RFEs data could be observed. Field experience learns that this was probably caused by the importance of local orographic rains as a result of the particular location of the Abiy Adi station at the foot of a steep mountain slope which rises 700 m high.

Increasing the accuracy of RFEs data for the North Ethiopian highlands was done by calibrating the RFEs with MS data. Therefore, a stepwise multiple regression analysis through the origin with RFEs, elevation, slope and slope aspect as independent variables and MS as dependent variable was applied (Purevdorj et al., 1998; Weisberg, 2005). Elevation, slope gradient and slope aspect were generalized from the 90 m SRTM (CGIAR, 2012) with the spatial analyst tools in ArcGIS® 9.2. These additional parameters were added to the regression analysis with the purpose of improving the estimation of the spatial variation of rainfall in the study area by the RFEs. The additional parameter slope aspect can take all trigonometrical directions and is therefore fitted according to the model of Nyssen et al. (2005) with a sinusoidal function. The spatial variation was modeled by a non-linear multiple regression according to a stepwise model, excluding at each step the least significant explanatory variable until the best significant relation was found.

The regression equation for the calibration is thus formed by:

$$\hat{M}s = \hat{\beta} \times RFE_i + \hat{\alpha} \times S_i + \hat{\mu} \times E_i + p_1 \times (\sin(A_i - p_2)) \quad (1)$$

with: $\hat{M}s$: estimate monthly MS rainfall (mm mth^{-1}); RFE_i: monthly RFEs rainfall (mm mth^{-1}); S_i: Average slope gradient of the pixel(°); E_i: Average elevation (m a.s.l.)

A_i: Average slope aspect (in deg. turning right from the N); p_1 and p_2 are constants: p_1 p_1= amplitude of the sinusoidal function and p_2 p_2= aspect (in deg.) where average rain is expected.

The obtained calibration function is cross-validated with a robust linear model (RLM) in R® 2.14.0. The ability of the RLM function to reproduce the observed MS rainfall, in comparison to a linear model, is tested with a jackknife function.

The cross-validated calibration function was used to calibrate the monthly RFEs images over the period 1996-2006 in ArcGIS® 9.2, using a raster query. Summing up calibrated rainfall values per year gave pixel-based annual rainfall and allowed to produce an isohyet map over the period 1996-2006.

Explaining the spatial variability of annual rainfall

The calibrated rainfall images were used to study the explaining value of five spatial parameters (elevation, slope gradient, slope aspect, easting and northing) on the spatial distribution of rainfall for the study area (eq. 2).

RFEcal = f(elevation, slope, slope aspect, easting, northing)? (2)

The calibrated RFE images have a resolution of 8x8 km^2, the SRTM derived parameters (elevation, slope and slope aspect) are therefore generalized to this resolution. Subsequently a vector point grid was computed for the center of the raster area and the pixel values were extracted for each point of all variables. The easting and northing of the pixels were calculated by adding x,y coordinates to the vector point grid. The results of these calculations in ArcGIS 9.2 are six corresponding tables. These were used as input to a multiple non-linear regression analysis to identify which variables do significantly explain the variability of annual rainfall in the study area.

7.3 Results

7.3.1 Monthly Rainfall Estimates versus Meteorological station data

Average monthly rainfall from the sixteen MS was 85.0 mm and 79.4 mm over the periods 1996-2000 and 2001-2006 respectively (Table 7.1, Figure 7.5). Over the same periods, average monthly rainfall derived from RFEs was 68.3 mm (RFE 1.0) and 59.8 mm (RFE 2.0). This means that RFEs underestimate by approximately 25% the rainfall recorded in MS. This is the result of extremely greater observations for the MS datasets (Table 7.1, Figure 7.5). The Pearson's *r* correlation coefficient is 0.85 between MS and RFE 1.0 and 0.80 between MS and RFE 2.0. Both the skewness and kurtosis are significant at the $\alpha = 0.05$ level.

Table 7.1 MS and RFEs monthly rainfall (mm mth-1) over the period 1996-2006.

	Period 1996-2000		Period 2001-2006	
	MS	RFE 1.0	MS	RFE 2.0
Months (*n*)	359	359	552	552
Mean	85.0	68.3	79.4	59.8
Median	45.6	32.0	43.0	39.0
Std Deviation	96.4	81.6	85.5	60.9
Minimum	0.0	0.0	0.0	0.0
Maximum	480.7	325.0	405.3	284.0
Interquartile Range	121.3	91.0	104.6	67.0
Skewness†	1.4	1.3	1.3	1.4
Kurtosis†	1.3	0.5	1.1	1.3

† significant at α = 0.05.

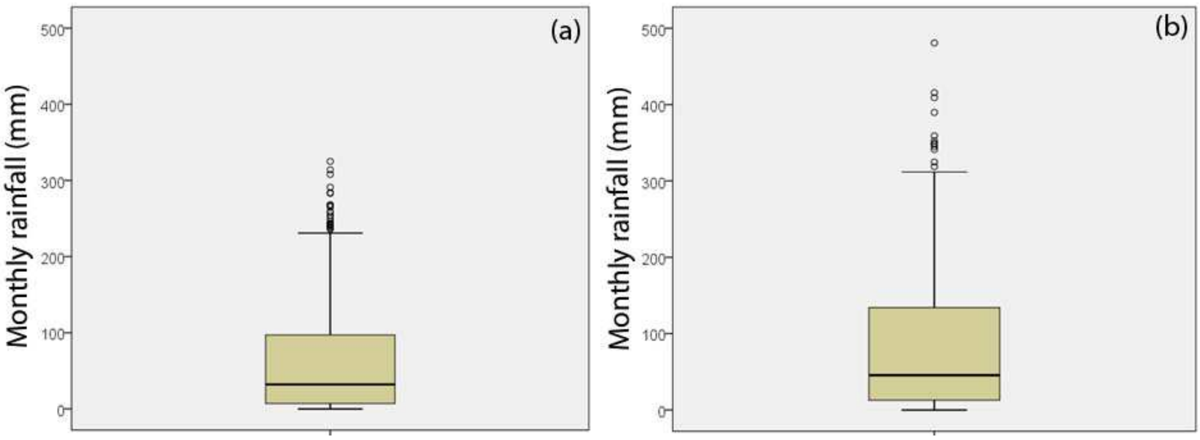


Figure 7.5 Boxplots of the monthly rainfall data (in mm) for the period 1996–2000 (a) RFE1.0 and (b) MS.

A linear regression analysis between monthly rainfall from MS and RFE 1.0 or RFE 2.0 was carried out to define the estimation accuracy of the RFEs (Figure 7.6A and B). With adjusted R^2-values of 0.72 and 0.64 respectively (P<0.001), both RFEs 1.0 and RFEs 2.0 prove to be good estimators of MS data. The validity of these models was supported by a fulfillment of the homogeneity of variance**,** normal distribution of the residuals, and no trends occurring when plotting the residuals against calendar years. From the line of prefect agreement (1:1 line; Figure 7.6A and B) it appears that RFEs generally underestimate MS rainfall, and the scatter around the trendlines indicates that the estimation of monthly rainfall by the RFE can be in gross error.

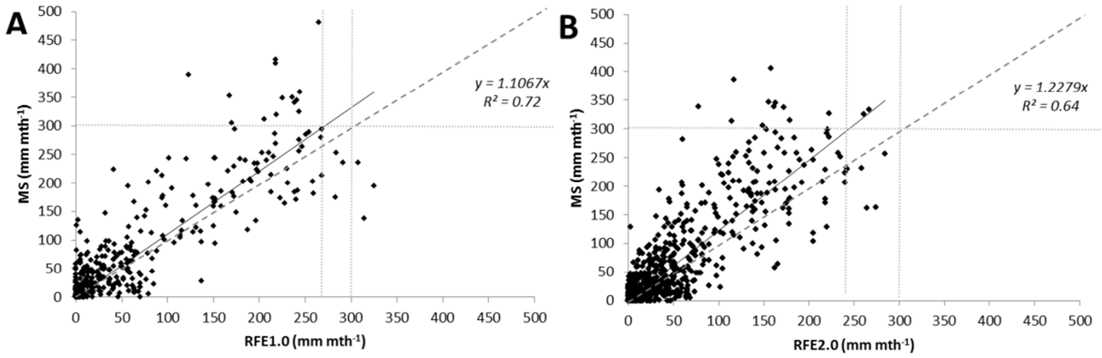


Figure 7.6 Linear regression analysis of monthly rainfall for RFEs versus MS. (a) RFEs 1.0 (period 1996–2000), (b) RFEs 2.0 (period 2001–2006). Underestimation of the RFE values in comparison to 300 mm monthly rainfall in MS.

7.3.2 Calibrated monthly Rainfall Estimates over the period 1996-2006

Slope gradient and slope aspect have no added value as explaining factors of the spatial variation and are therefore excluded from the regression equation (Table 7.2). Elevation is significant but the explaining value gained by adding this variable in the regression equation is very low (R^2 increases by 0.009). The stepwise regression finally resulted in a simple linear regression through the origin (0,0) with RFE as independent variable.

Table 7.2 Coefficients and excluded variables as resulted from the non-linear multiple stepwise regression (RFE1.0, 1996-2000)

	t	Sig.
Coefficients		
RFE1.0	31.500	0.000
Elevation	4.832	0.000
Excluded variables		
Slope gradient	-0.243	0.808
Slope aspect	-0.071	0.944

The linear model (LM) is cross validated with a robust linear model (RLM). The fitted regression line of the LM and RLM function are almost identical, the RLM fitted line falls completely within the 95% confidence interval of the LM (Figure 7.7).

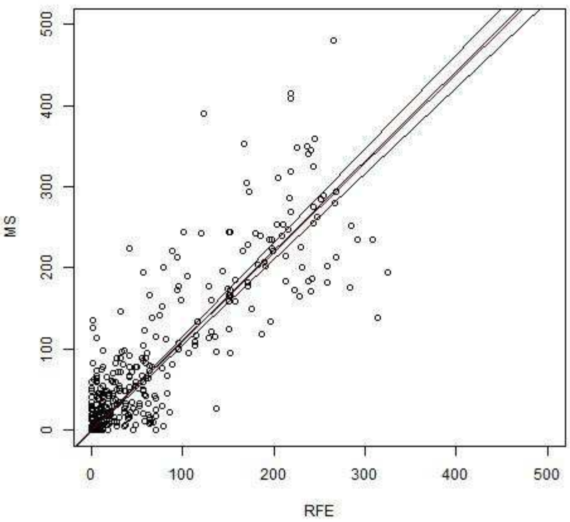


Figure 7.7 A comparison between LM and RLM for RFE1.0 versus MS (1996–2000). Black, the fitted regression line of the LM with 95% confidence interval (CI); red, the RLM fitted regression line. Note that the red RLM regression line lies completely within the 95% CI of the LM.

The jackknife estimate of bias for the LM and RLM is respectively 0.001 and -0.012 and the jackknife estimate of the standard error is respectively 0.038 and 0.042. The difference between the jackknife estimate of the bias and standard error is insignificant. Therefore the LM is used for the calibration for the two RFE versions 1.0 and 2.0 separately.

As the RFEs prove to underestimate monthly MS rainfall, a linear regression analysis with RFEs as independent variable and MS as dependent variable was performed (Figure 7.6A and B). The linear regression equations for RFEs 1.0 and 2.0 were:

$$\hat{Ms} = 1.1067 \times RFE(1.0)_i \qquad R^2\text{: 0.72 N: 359 P: <0.001} \qquad (3)$$

$$\hat{Ms} = 1.2279 \times RFE(2.0)_i \qquad R^2\text{: 0.64 N: 552 P: <0.001} \qquad (4)$$

As both coefficients were significant at P<0.001, calibrating the RFEs images was done by multiplying the RFEs pixel-values with 1.1067 and 1.2279 for RFEs 1.0 and RFEs 2.0.In order to validate the calibration model, a comparison of the original RFE values and the calibrated RFE values to the MS gauge rainfall values is made. As a result of the RFE1.0 calibration, the estimation of rainfall for the study area improved by average with 8% (Table 7.3) in comparison to the original RFE1.0.

Table 7.3 Validation of calibration model for RFE1.0 (1996-2000)

	Total†			Error§		Improvement¶ of
	Orig. RFE (mm)	*Gauge Rainfall (mm)*	*Cal‡ RFE (mm)*	*Orig. RFE (%)*	*Cal RFE (%)*	*Cal RFE (%)*
March	897	1455.3	992.7	38.4	31.8	6.6
April	1109	1489.0	1227.3	25.5	17.6	7.9
May	1161	2051.7	1284.9	43.4	37.4	6.0
June	1516	2039.8	1677.8	25.7	17.7	7.9
July	8861	10635.5	9806.5	19.3	7.8	8.9
August	9797	10993.1	10842.3	8.6	1.4	9.5
September	1161	1838.5	1284.9	36.9	30.1	6.7
Avg. total	3500	4357.6	3873.8	28.2	20.5	7.7%

† Rain season total
‡ Calibrated RFE: 1.1067*RFE1.0
§ Percentage error in comparison with MS
¶ Improvement of calibrated RFE in comparison with original RFE

The monthly calibrated RFE images are summed for each year to obtain maps of the total yearly rainfall (Figure 7.8). The calibrated RFE maps demonstrate regional and temporal yearly rainfall contrasts for the study area. Based upon these maps an isohyet map of the average yearly rainfall for the period 1996-2009 was constructed (Figure 7.9).

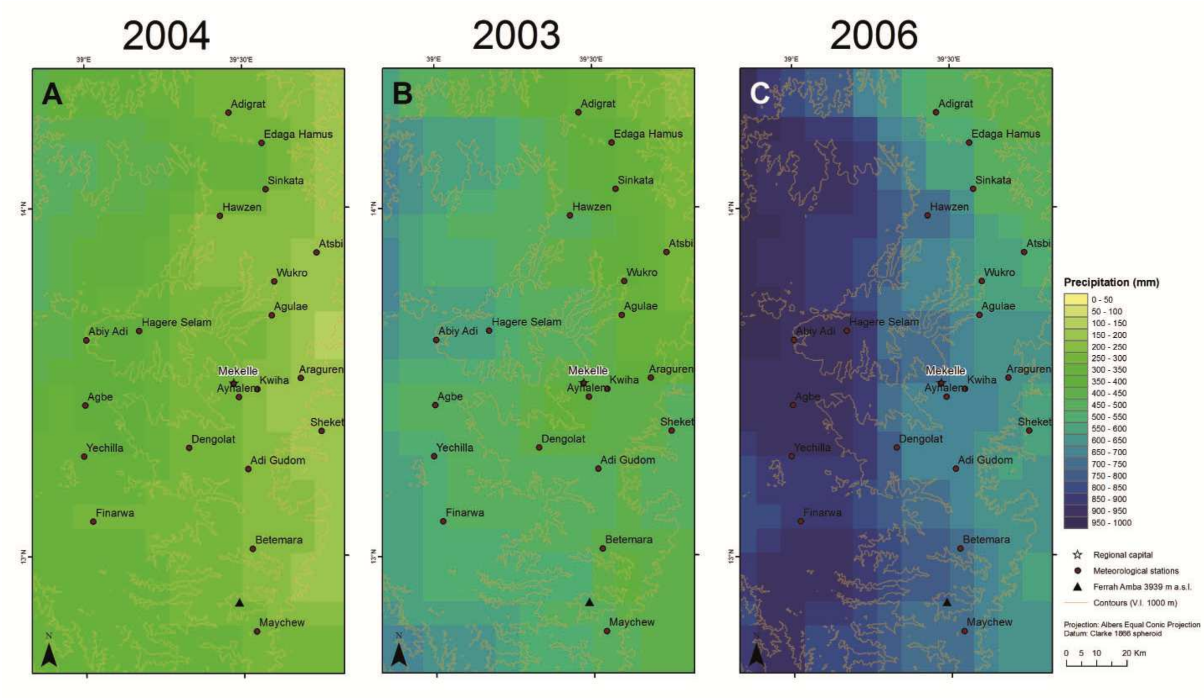


Figure 7.8 Calibrated yearly RFEs corresponding to a typical (a) dry year (2004), (b) normal year (2003), and (c) wet year (2006).

The isohyet map indicates that there is a general northeast-southwest gradient of increasing rainfall in the study area and a sharp east-west gradient of increasing rainfall in the north of the study area. The average annual rainfall of the southernmost MS of Maychew is only 542 mm. The average total rainfall difference between the northeastern (320 mm) and the southwestern (620 mm) part of the study area is 300 mm. However this difference fluctuates highly between the different observed years.

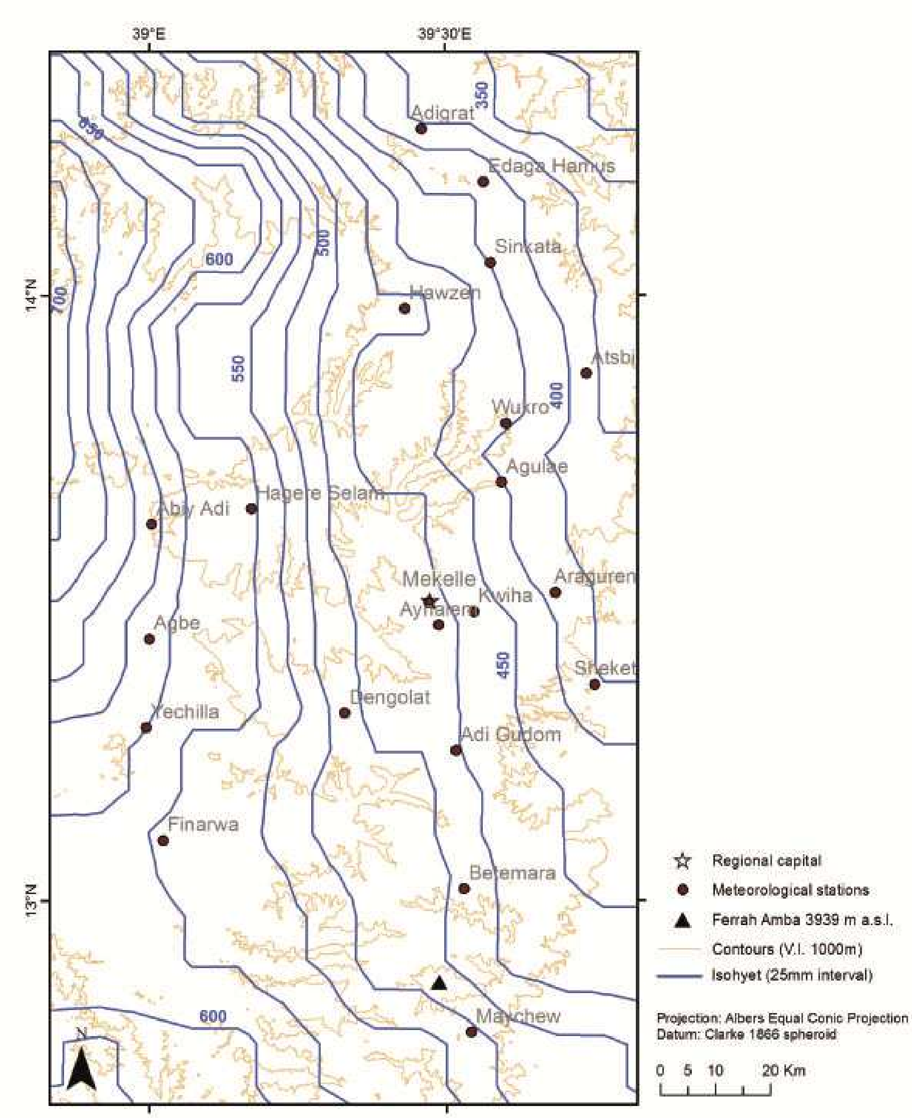


Figure 7.9 Isohyet map of average rainfall (1996–2006) in the rainy season (March–September) as derived from calibrated RFE data.

7.3.3 Spatial variability of annual rainfall

A non-linear multiple regression is used to determine which variables are significantly explaining the variability of the annual rainfall. The regression is executed with the calibrated average of RFE1.0 as dependent variable (representing the spatial distribution of rainfall) and elevation, slope gradient, slope aspect, easting and northing as independent explaining variables. The stepwise multiple regression excludes the variables elevation, slope gradient and slope aspect, these variables are not significantly contributing in explaining the spatial distribution of the rainfall. The resulting regression equation includes easting and northing (eq. 5) and has an R^2-value of 0.86 (P<0.001). The distribution of rainfall for the study area is thus very dependent on easting and northing.

$$\text{RFEcal} = 7333.581 - 0.00288029E - 0.000663432N \qquad R^2\text{: } 0.86 \text{ N: } 325 \text{ P:} <0.001 \quad (5)$$

With
E: Easting (m)
N: Northing (m)

A simple linear regression analysis between successively easting- and northing- and RFEcal average (1996-2000) is given in Figure 7.10A and B. Apparent is the high explaining value of the easting (R^2: 0.72). The east-west position is hence most important in explaining the amount of yearly rainfall for the study area. The amount of rainfall decreases eastwards. The explaining value of the northing is less strong (R^2:0.14), however the plotted linear trendline shows a decrease of rainfall with increasing northing. These results correspond to the trends detected from the calibrated rainfall maps (Figure 7.8).

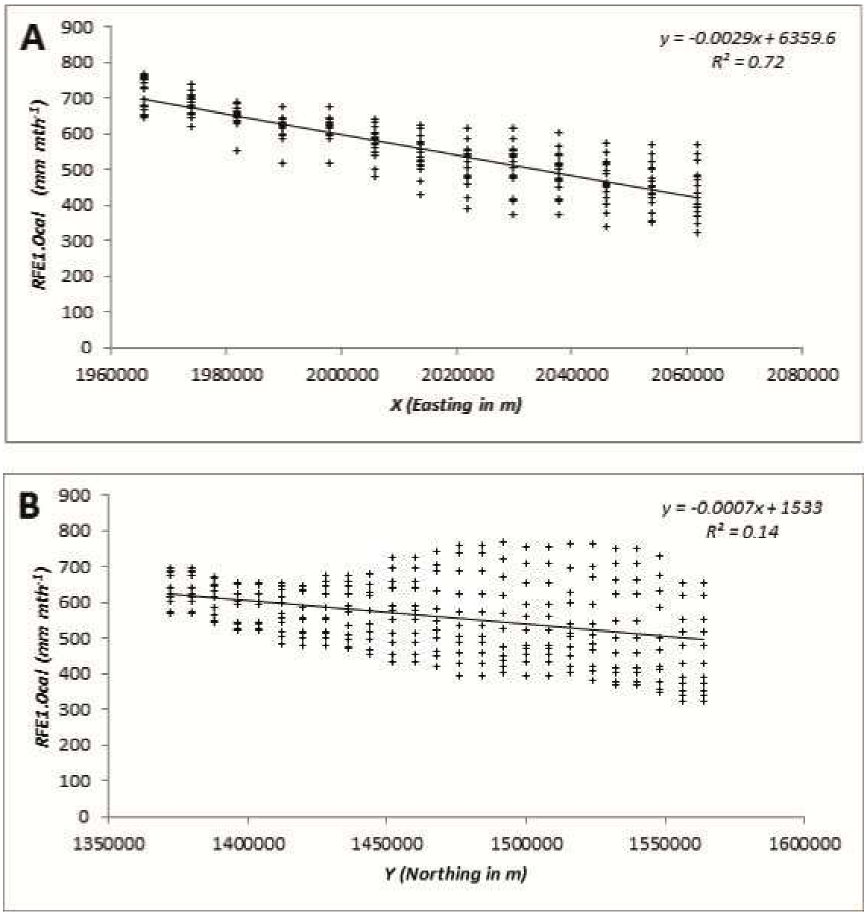


Figure 7.10 Linear regression analysis of longitude (A) and latitude (B) versus average annual calibrated rainfall of RFE1.0 (1996–2000) (RFE1.0cal).

7.4 Discussion

As indicated by this and previous studies (Beyene and Meissner, 2010; Dinku et al., 2007), RFEs can provide fairly good insights into spatiotemporal rainfall patterns in North Ethiopia. The high correlation coefficients of 0.85 or 0.80 between monthly rainfall from MS and RFEs 1.0 or 2.0 respectively are similar to the findings of Dinku et al. (2007) were *r*-values of 0.78 and 0.75 are reported. RFE1.0 is performing 8% better than the new RFE2.0 images that seems to suffer from the exclusion of orographic warm rain processes in the RFE2.0 algorithm (Beyene and Meissner, 2010). High correlations were found during the rain season (March-September) and weak correlations occurred during the dry season (October-February). To counter the weak correlation in the dry season, only the rain season rainfall from March till September is used in the calibration model. Neglecting the dry season rainfall is possible given its limited fraction of the annual rainfall (*ca.* 9%) in the North Ethiopian highlands.

RFEs underestimate precipitation (Dinku et al. 2007; Figure 7.6). According to Dinku et al. (2007) this is especially the result of an important underestimation of large precipitations. The patterns of the isohyet map match patterns as described in literature (Degefu, 1987; Tadesse et al., 2006). The calibration model succeeds to reduce the error scatter of the original RFEs, but an underestimation of rainfall remains. The study of Dinku et al. (2010), revealed that RFE exhibit moderate underestimations of rainfall over mountainous regions. This is also apparent in our study, especially in the southern part of the study area. The average annual rainfall of Maychew is according to the isohyet map 542 mm, but in actuality (according to the MS data) 661 mm. Rainfall in the south is thus strongly underestimated, by 119 mm for Maychew. The poor calibration in the south may also result from the very limited rainfall data available for the southern stations of Yechilla, Finarwa and Betemara. In the western MS of Agbe the annual average rainfall differs only 4 mm between the RFE average (610 mm) and the actual MS average (614 mm).

The spatial variability of rainfall in the study area is mainly determined by easting and only very limited by northing. Nonetheless northing - as a result of the northwards movement of the ITCZ - is generally described as the most important explaining factor for the distribution of rainfall in Ethiopia (Goebel and Odenyo, 1984; Krauer, 1988). This contrast results from the location of the study area at the boundary of the Rift Valley. The general rainfall pattern is modified by the topographic boundary of the Rift Valley (Degefu, 1987) and as a result the rainfall pattern of the study area is dominated by a sharp east west gradient of increasing rainfall. The scatter around the trendlines for easting increases east and for northing increases north; this indicates that rainfall variability increases in drier regions.

To further improve the reliability of the RFE calibration, additional mountain related rainfall data is necessary. This could be achieved through densification of the rain-gauge network with new MS measuring rainfall in mountainous regions. An interesting perspective for future research consists of an historical extrapolation of the spatial rainfall pattern. We would suggest a reconstruction back to the 1970s, as rainfall measurement for most of the MS starts from this period (Figure 7.3).

7.5 Conclusion

The semi-arid to subhumid mountain climate with unimodal rainfall patterns of the North Ethiopian highlands is especially vulnerable to rainfall anomalies. The rainfall estimation strength of satellite derived RFEs for the study of spatio-temporal rainfall patterns is validated to MS data with a linear regression through the origin (0,0). As a result of a weak correlation between RFE and MS rainfall data in the dry season (R^2:0.26), only the rain season from March till September is analyzed (responsible for *ca*. 91% of the annual rainfall). The result demonstrates that the RFEs are well correlated with the MS rainfall data (85% and 80% for RFE 1.0 and 2.0 respectively). Nevertheless RFEs generally underestimate MS rainfall and scatter around the trendlines indicate that the estimation can be in gross error. To improve the RFEs for the mountainous study area, a calibration with local rain gauge data and explanatory spatial parameters was applied. The SRTM derived spatial parameters (elevation, slope gradient and slope aspect) were not significant. Consequently the calibration resulted in a linear regression through the origin (0,0) with MS as dependent variable and RFE as independent variable. Based upon the calibration model the estimations of the RFEs improved with 8%. The calibrated RFEs supported the production of annual rainfall maps for the study area and an isohyet map with the average yearly rainfall for the period 1996-2006. The maps indicate that there is a general northeast-southwest gradient of increasing rainfall in the study area and a sharp east-west gradient of increasing rainfall in the north of the study area. The explanatory value of slope, elevation, slope aspect, easting and northing for the spatial variability of annual rainfall is studied in a non-linear multiple regression with the calibrated RFE as dependent variable. Of the explanatory variables only easting and northing are significant and included in the regression analysis (R^2: 0.86). The most important explaining variable of the spatial rainfall variability is easting (R^2: 0.72). This results from the position of the study area at the boundary of the Rift Valley. The scatter around the individual trendlines of easting and northing demonstrate that rainfall variability increases in drier regions. Based upon the calibration model the scatter of the original RFEs can be reduced, but an overall underestimation of rainfall remains. The high underestimation of rainfall in the south of the study area is possibly the result of the more pronounced relief. In order to make RFEs more reliable, especially in mountainous areas, additional mountain related MS rainfall data is necessary to improve the calibration of the RFE images. However calibration of RFEs for the study area has proven to be valuable in gaining improved understanding of the regional spatiotemporal rainfall patterns, which are important as input to a wide range of scientific models with direct linkage to land management strategies and scenarios.

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Chapter 8 Microclimate conditions for *Erica arborea* growth at the upper treeline in Northern Ethiopia

This chapter is based on:

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Abstract

The microclimatic conditions in the tropical African highlands determine the growth limitations for the vulnerable afro-alpine vegetation and the treeline forest. In this chapter, the determining factors of the mountain microclimate are studied at the afro-alpine *Erica arborea* treeline for two mountain ranges in North Ethiopia: Lib Amba of the Abune Yosef Mts. and Ferrah Amba Mt. Rainfall, air, ground and soil temperature are measured between March 2012 and October 2014 in local meteorological stations installed along the slope of these mountain ranges. Rainfall, ground and soil temperature have no significant relation with altitude. Rainfall follows a bimodal rainfall pattern with an unreliable small rain season (March-May) preceding the main rain season (June-September). The soil temperature is influenced by vegetation cover and incoming radiation. Soil temperatures (-12 cm) in forested areas are on average 1.8°C colder in comparison to non-forested areas. This can cause a positive feedback effect by the forest, sheltering tree seedlings against diurnal soil temperature variability. Air temperature is strongly related with altitude. The average environmental lapse rate in the study area is 0.72°C per 100 m. Air temperature is indicated to be most important in setting the treeline limit in the North Ethiopian highlands. The treeline is currently located 400 m below its climatic potential limit and is expected to increase 150 m in elevation under a climate warming of 1°C.

Keywords: Microclimate; positive feedback; environmental lapse rate; potential climatic treeline

8.1 Introduction

High mountain areas and the ecological transition zone of the treeline in particular, are sensitive ecosystems to a great extent, controlled by climate (Bendix and Rafiqpoor, 2001; Bader et al. 2007). Climate is a key factor regulating tree growth. The prevailing climatic conditions set limits for tree survival, for species composition and stand characteristics (Wieser and Tausz, 2007).

Barry (2008) gives a review of the four basic geographical determinants of mountain climates: latitude, altitude, topography and continentality. The latitude effect explains the low seasonal variability in day-length and solar radiation totals in the tropics. The annual range of extraterrestrial radiation is only 19% at 10°, whereas this increases up to almost 400% at 50° (Sarmiento, 1986). In the tropics, the daily temperature amplitutde is generally larger in comparison to the seasonal variation. For tropical regions under the influence of the movement of the Intertropical Convergence Zone (ITCZ), the seasonal rainfall pattern is also driven by the passage of the sun (Sarmiento, 1986). The annual rainfall pattern influences the temperature regime. In the dry season, cloudiness is low and dry atmospheric conditions lead to high day and low night temperatures. While in the rain season, daily temperature fluctuation is generally lower due to increased cloudiness limiting solar radiation during the day and high relative humidity during the night limiting coldness by longwave outgoing radiation (Sarmiento, 1986). Of primary importance for the mountain climate are altitudinal differences. Air pressure and density decrease with increasing altitude. Vapor pressure is important because it reduces the infrared and solar radiation, influences the saturation deficit and inversely the total air density, which causes reduced temperatures. The decrease of temperature with height is defined as the environmental lapse rate, i.e. 6°C per km^{-1} in the free atmosphere (Barry, 2008). Beside altitude, the mountain climate is also strongly influenced by the topography. Slope and aspect cause spatial contrasts in solar radiation, temperature and precipitation regimes (Barry, 2008). In addition, the vegetation cover has a strong influence on microclimate conditions. The vegetation cover modifies the heat balance received by the land surface, indirectly through the obstruction of incoming and outgoing radiation and directly through modification of humidity and temperature (Hertel and Wesche, 2008).

In general, differences in heat deficiency cause a higher treeline in the subtropical mountains and a decrease of the treeline towards the equator and to higher latitudes. The treeline elevation can, however, not only be attributed to differences in thermal conditions. Precipitation can also act as a critical limiting factor in semi-arid areas (Holtmeier, 2009). Air and soil temperature and precipitation and cloudiness are key climate factors for tree growth at the treeline elevation in the tropics (Chapter 2). The control mechanisms of tree growth at the African tropical treeline are however, still poorly understood (Körner and Hoch, 2006; Körner, 1998; Smith et al., 2003; Tranquillini, 1979). Climate mechanisms for tree growth are more widely studied at the treeline in the tropical Andes (Bader, 2007; Bendix and Rafiqpoor, 2001; Cavieres et al., 2000; Ellenberg, 1996; Sarmiento and Frolich, 2002). In the tropical highlands of South America excess solar radiation, low night temperatures and soil temperature are important climatic factors controlling tree growth at the treeline, besides fires (Bader, 2007).

However, there is still uncertainty about the different effects of soil, air, average and extreme temperatures on limiting tree growth at the treeline (Körner and Hoch, 2006; Körner, 1998). In general, the average air temperature at the treeline is found to correspond with approximately 6-8°C outside the tropics and around 5°C in the tropics (Körner, 2012). The soil temperature within the rooting zone is decisive for plant growth and survival. Tree seedlings commonly root in the upper 10 to 20 cm of the soil (Holtmeier, 2009). Low soil temperatures shorten the growing season and impede important process in the plant (e.g. photosynthesis, root respiration, root growth, decomposition, nutrient uptake). Soil temperature decreases with elevation, but with a lower rate than air temperature. As a result, the thermal gradient between the soil surface and air temperature increases with elevation. To cope with this, low growth is observed in the upper treeline ecotone (Holtmeier, 2009). Tree growth at the treeline is found to be correlated with a mean soil temperature at -10 cm of 6.1°C ± 0.7°C during the growing season or 6.7°C ± 0.8°C all year round in the tropics (Hoch and Körner, 2003; Holtmeier, 2009). The complex climate of the Ethiopian highlands is characterized by unreliable seasonal rainfall (Chapter 7). Rainfall is mainly dependent on the movement of the Intertropical Convergence Zone (ITCZ) (Ogallo, 1989). From June to September this ITCZ is in its most northern position inducing the rain season responsible for 65-95% of the total annual rainfall (Segele and Lamb, 2005). The rain season is followed by a long period of drought from October to February. The aim of this chapter is to understand what factors are impeding rainfall, air, ground and soil temperature in tropical mountains, based on a detail study in the North Ethiopian highlands, and to disentangle the complex relation between the mountain climate and the afro-alpine treeline elevation.

8.2 Method

8.2.1 Study area

The study area consists of three mountain ranges in the North Ethiopian highlands. The Simen Mts., home to the highest peak of Ethiopia (Ras Dejen Mt., 13°16’N, 38°24’E, 4540 m a.s.l.); Lib Amba Mt. (12°04’N, 39°22’E, 3993 m a.s.l.) of the Abune Yosef Mts.; and Ferrah Amba Mt. (12°52’N, 39°30’E, 3939 m a.s.l.) (Figure 8.1). The mountain climate of the Simen massif is described by Hurni and Stähli (1982) based on a meteorological station in Gich camp at 3600 m a.s.l. A similar baseline study is missing for the other mountain areas. For the Abune Yosef mountain range meteorological data are collected by the National Meteorological Agency (NMA) in Lalibela (at 2447 m a.s.l.) and in Muja (at 2800 m a.s.l., only rainfall), for Ferrah Amba this is in Maychew (at 2408 m a.s.l.) and Adishiho (at 2489 m a.s.l., only rainfall) and for Simen in Debark (at 2855 m a.s.l.). Meteorological data for areas above 2500 m is thus limited outside the Simen Mountains and even for the Simen Mountains there is no long-term data collection above 3000 m. The afro-alpine treeline vegetation at this elevation is dominated by *Erica arborea*. When left unburnt, *Erica* grows to tree-size at this elevation, even on very thin soils (Egziabher, 1988).

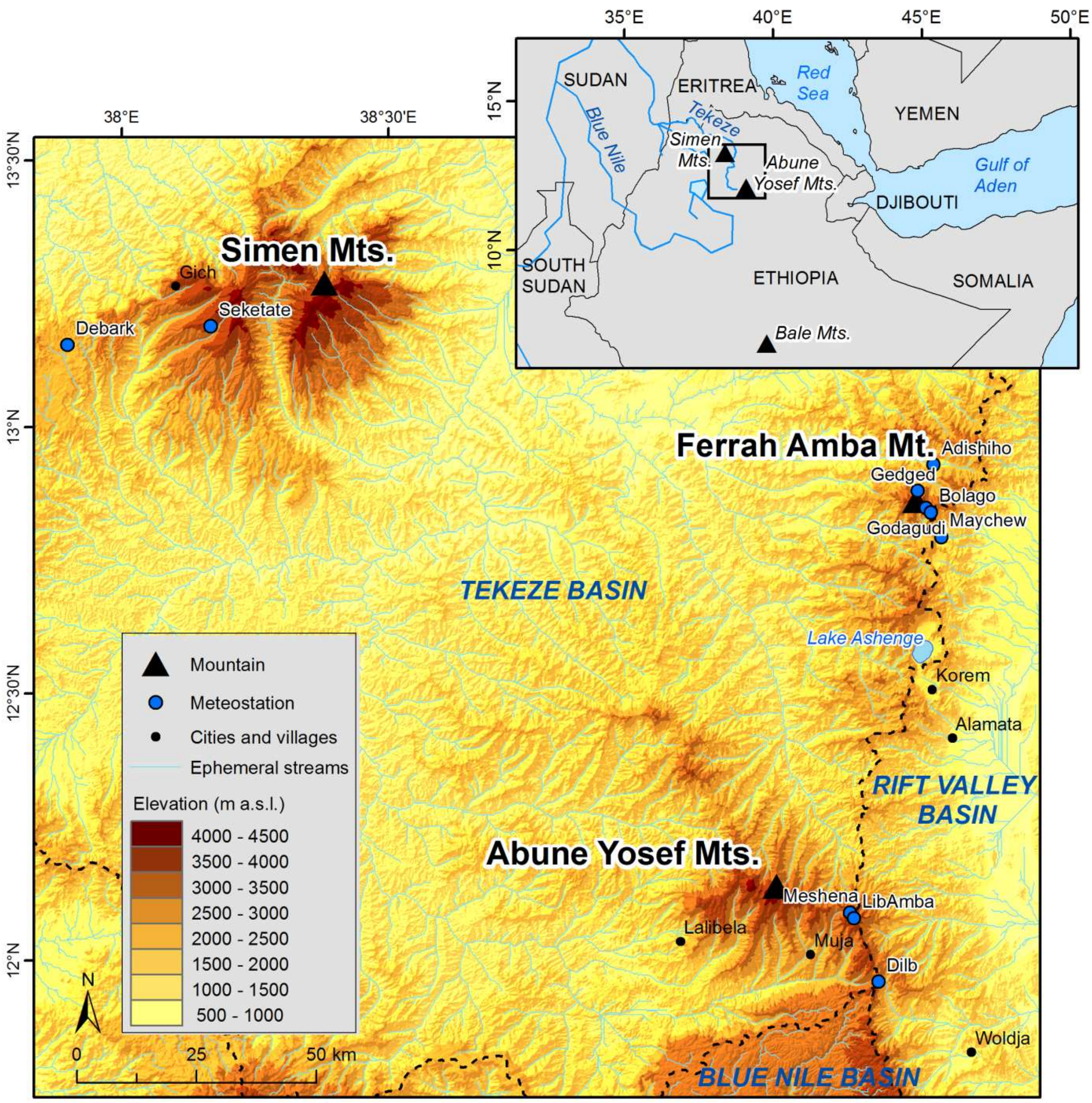

Figure 8.1 Location of the study area with locations of the meteorological station indicated with blue dots

8.2.2 Data collection

For this study, 10 basic meteorological stations were installed along the slopes of the mountain study sites (Figure 8.2). In these stations the minimum and maximum air temperature and rainfall were measured (Figure 8.3A,B) on a daily basis from March 2012 to October 2014. In Ferrah Amba five stations were installed: three at the southern slope in Maychew (2408 m a.s.l.), Bolago (2975 m a.s.l.) and Godagudi (3477 m a.s.l.) and two at the northern slope in AdiShiho (2489 m a.s.l.) and Gedged (3393 m a.s.l.). In Lib Amba two stations were installed at the northern slope in Meshena (3471 m a.s.l.) and above Meshena at 3641 m a.s.l. and one station was installed 10 km southwards in Dilb

(3268 m a.s.l.). In the Simen Mountains two stations were installed, one in Debark (2855 m a.s.l.) and one in Seketate (3660 m a.s.l.), however data collection in Seketate failed. The stations in Maychew, Adishiho, Dilb and Debark were installed near the location of an NMA station for sake of calibration.

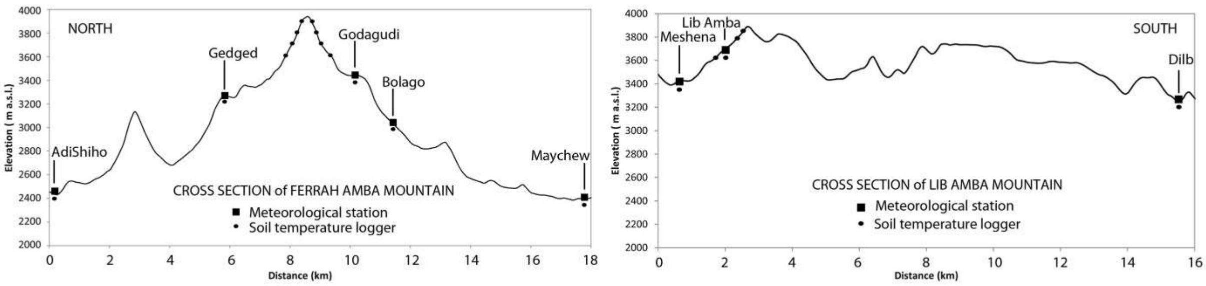

Figure 8.2 Schematic representation of the distribution of the meteorological stations and soil temperature loggers on a profile of the mountain (a) Ferrah Amba and (b) Lib Amba

Figure 8.3 (A) Rain gauge in Gedged, (B) Stephenson screen with a min-max thermometer inside in Godagudi and (C) soil temperature loggers fixed to a pvc tube at the top (-2 cm) and 10 cm lower (-12 cm), ready for installation in the soil.

The variation of the climate factors with altitude is important since it sets the tree growth and thus treeline limit. Therefore, emphasis is given to the altitudinal gradient of air and soil temperature and rainfall variability. For illustration of this gradient with elevation, the explanatory variable elevation is given on the y-axis of scatterplot graphs.

In addition, soil temperature loggers (Figure 8.3C) were installed along the mountain slopes at ground level (-2 cm) and at -12 cm. The loggers were distributed on vertical transects crossing the afro-alpine grassland and the upper forest (Figure 8.2). Two types of loggers were used: iButtons DS1922L (Thermodata Pty Ltd.) and HOBO U23-series (Onset Computer corporation). In deep boreholes soil temperature loggers are commonly installed inside a plastic tube (e.g. Johansson et al. (2011). In this study, a similar plastic tube was used, but the loggers were fixed on the outside to keep them in direct contact with the soil. The iButtons were programmed to record temperature every 2h24min, which corresponds to 10 records a day; the HOBOs measured temperature at a one hour interval. These loggers collected soil temperature data during one year, from September 2013 until August 2014.

8.3 Results

The average (2012-2014) rainfall and temperature data of the meteorological stations are visualized in ombrothermic diagrams (Figure 8.4). Rainfall is mainly concentrated in July-August (peak of the rain season) and is very low from October to February (dry season) for all stations. Annual rainfall in Debark is much higher in comparison to the other stations. The air temperature is relatively stable throughout the year and does not drop below zero for all stations.

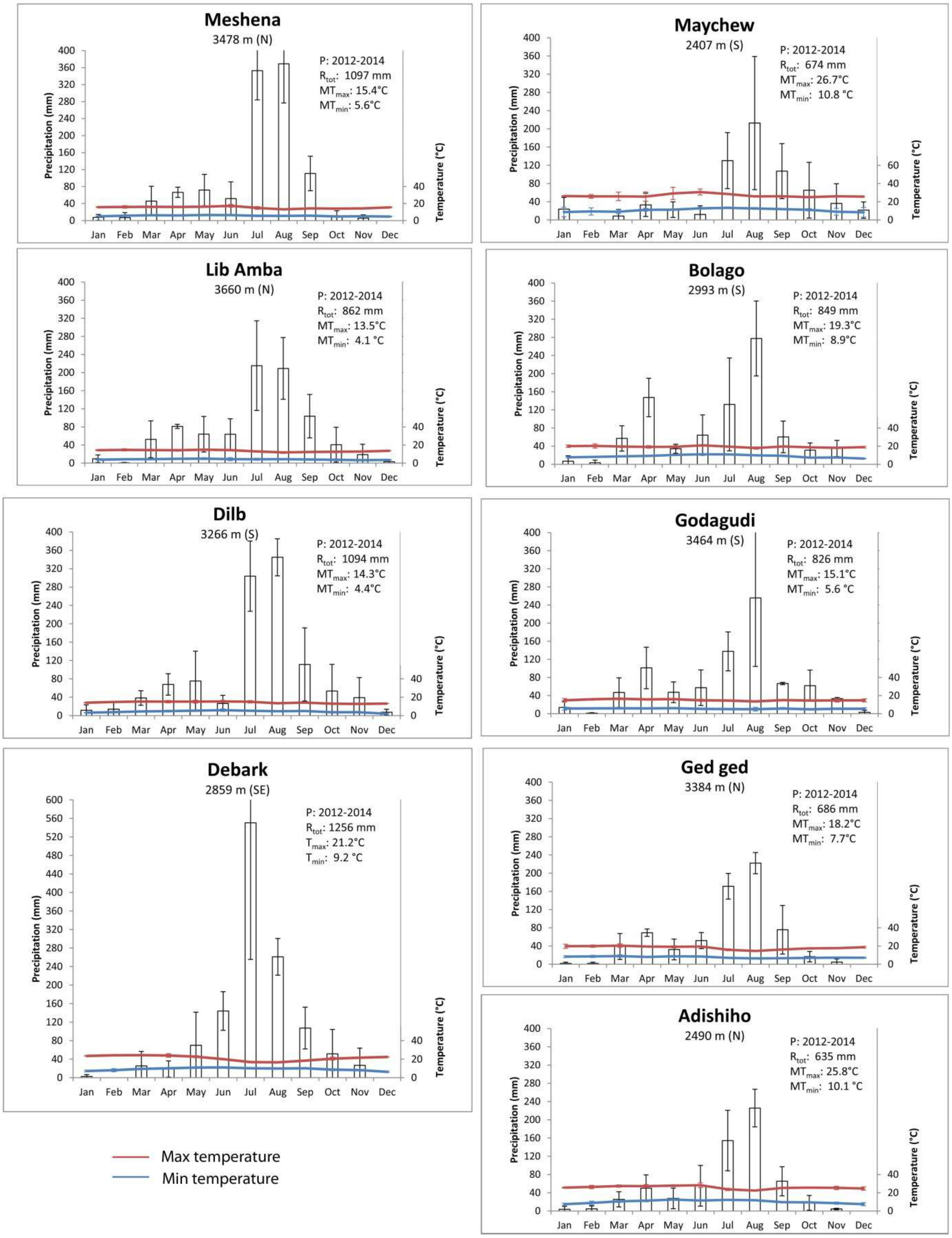

Figure 8.4 Ombrothermic diagrams of the meteorological stations for the average monthly rainfall and temperature (2012-2014). P: Period; Rtot: mean total annual rainfall; MTmax: mean maximum temperature; MTmin: mean minimum temperature.

8.3.1 Validation

A linear regression through the origin (0,0) was used to verify rainfall measurements in the meteorological stations using parallel rainfall measurements from the NMA stations in the direct vicinity (<1 km) (Chapter 7). The validation is limited due to the short period of overlapping measurements in combination with missing values in the NMA dataset. This is especially the case for the NMA station in Dilb, for which there are only four months of rainfall data available in 2013. Overall, the rainfall measurements fit well with the NMA measurements, the R^2 is respectively 0.88, 0.94, 0.92 and 0.98 for Maychew, Adishiho, Dilb and Debark (Table 8.1). This indicates that data collection in the meteorological stations was well performed and that the rainfall data can be used for further analysis. In Debark the measurements are close to the line of perfect agreement (1:1), whereas in Adishiho and Dilb rainfall is higher than in the NMA station and in Maychew rainfall is lower. These local differences are caused by the position of the station. For example, the station in Adishiho is located at the slope, whereas the NMA station is located in the valley bottom.

Table 8.1 Rainfall calibration between the station measurements and the NMA measurements

	2012	*2013*	*2012-2013*	*Regression equation*	*NMA data*
Maychew	0.95	0.89	0.88	$P_{MS} = 0.81\ P_{NMA}$	1992-2013
Adishiho	0.94	ND*	ND	$P_{MS} = 1.60\ P_{NMA}$	1955-59,63,65,66,98-2006, 2008,2012
Dilb	ND	0.92	ND	$P_{MS} = 1.39\ P_{NMA}$	2011, 2013(4)
Debark	0.96	1	0.98	$P_{MS} = 1.07\ P_{NMA}$	1980-83,85,87-88,92-2013

*ND: No Data

The NMA data were used to analyze the inter-annual (1992-2013) rainfall variability for the study area. In order to compare the variability of the different stations, the annual rainfall was normalized using z-scores of rainfall anomaly (Wu et al., 2001) (Figure 8.5). Because the data for Dilb is very scarce, the NMA station of Lalibela was added to the long term comparison. Most stations indicate a lower than average rainfall in the period 2012-2013. Exception is the higher than average rainfall in 2013 for Lalibela. The 5-year average trendline is given for the Maychew station. This trendline indicates that the period of measurements correspond with a period of decreased rainfall.

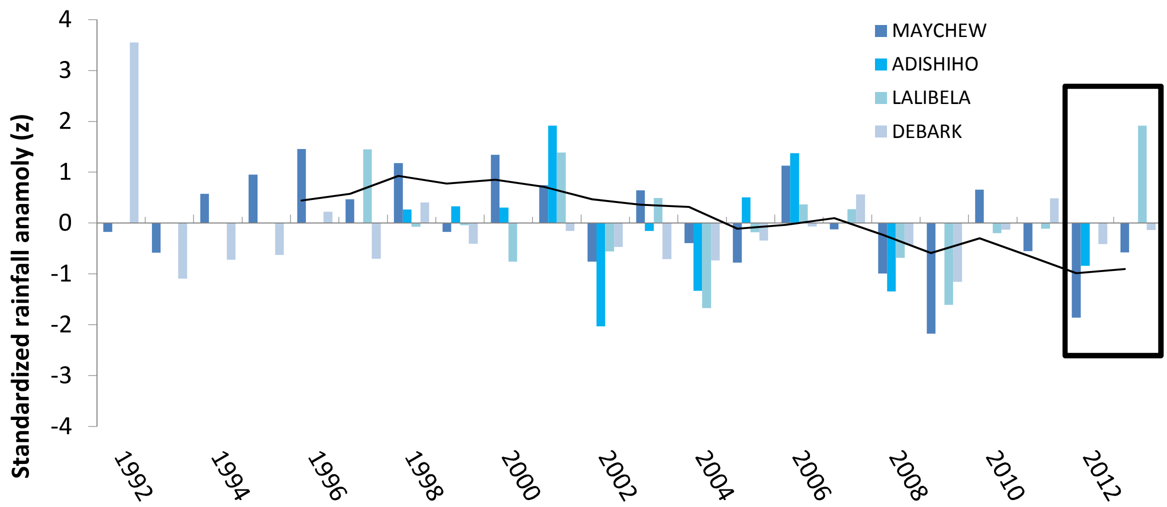

Figure 8.5 Standardized annual long-term rainfall anomalies for Maychew and Debark (1992-2013), Lalibela (1997-2013) and Adishiho (1998-2012). The 5-year average trendline is given for Maychew. The period corresponding with the meteorological measurements in the field stations (2012-2013) is indicated with a square.

8.3.2 Rainfall variability

Rainfall in the study area follows a bimodal rainfall pattern with a very unreliable azmera rainy season (in March-May) preceding the main kiremt rain season (in June-September) (Figure 8.6). Lib Amba receives on average 52% more rainfall during the kiremt rain season and approximately 300 mm more rainfall annually.

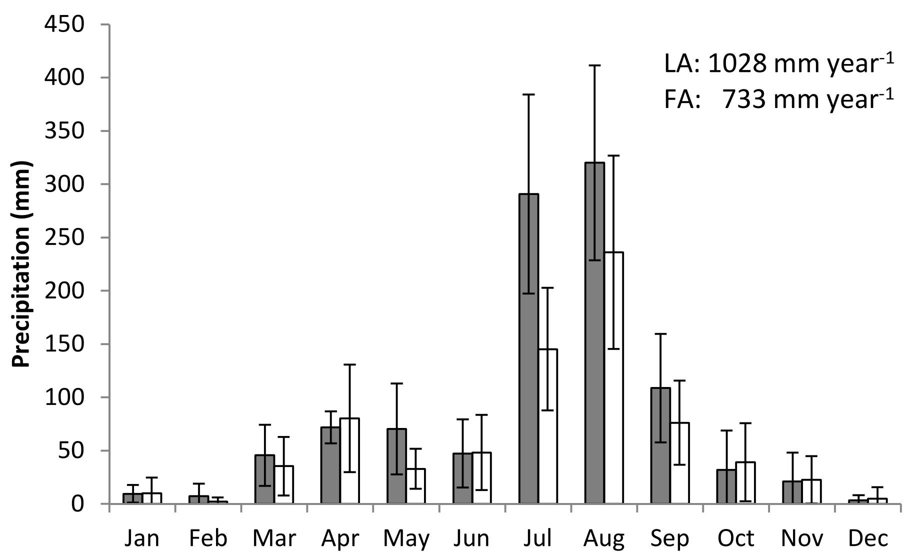

Figure 8.6 Average rainfall for Lib Amba (grey) and Ferrah Amba (white) (2012-2014). Both study areas have an unreliable short rainy season between March and June (azmera season), followed by the main rain season (kiremt season) between June and September.

Mean annual rainfall is highest for Debark with 1256 mm, of which 85% falls in the kiremt season (Table 8.2). Average annual rainfall amounts in Meshena and Dilb are also above 1000 mm, but these stations are located at higher elevations. In Lib Amba the difference in annual rainfall between the northern and southern side is small. Remarkably, rainfall in the upper stations is lower than at the lower stations. Rainfall tends to decrease with elevation near the top of Lib Amba, but more data is needed to confirm this pattern. Whereas annual rainfall in Ferrah Amba is higher on the southern slope and only slightly (35 mm) lower in the upper station of Godagudi (3477 m) in comparison to the lower station of Bolago (2975 m). The coefficient of variation (CV) is small for kiremt rainfall in most stations, except in Maychew. However the CV is much higher in the azmera season, indicating the unreliable nature of this rainy season in March-May. The vertical distribution of the average annual rainfall with altitude was analyzed using a linear regression (Figure 8.7). Rainfall tends to increase with elevation between 2000 and 3500 m a.s.l., but this relation is not significant (R^2: 0.28; p>0.05).

Table 8.2 Rainfall data

	Simen	*Ferrah Amba*					*Lib Amba*		
	DE	*AD*	*GE*	*GO*	*BO*	*MA*	*ME*	*LA*	*DI*
Slope aspect	*SE*	*N*	*N*	*S*	*S*	*S*	*N*	*N*	*S*
Elevation (m a.s.l.)	2855	2489	3393	3477	2975	2408	3471	3641	3268
MR_{annual} (mm)	1256	633	684	814	849	654	1095	785	1061
$CV(2012\text{-}2014)_{annual}$	0.14	0.15	0.11	0.23	0.17	0.40	0.05	0.11	0.09
MR_{kiremt} (mm)	1063	501	521	517	534	462	885	592	787
$CV(2012\text{-}2014)_{kiremt}$	0.16	0.12	0.09	0.43	0.15	0.50	0.11	0.14	0.15
MR_{azmera} (mm)	114	103	140	195	238	64	184	198	182
$CV(2012\text{-}2014)_{azmera}$	0.33	0.56	0.30	0.19	0.030	0.90	0.30	0.40	0.40

MR: Mean rainfall; CV: Coefficient of Variation; DE: Debark; AD: Adishiho; GE: Gedged; GO: Godagudi; BO: Bolago; MA: Maychew; ME: Meshena; LA: Lib Amba; DI: Dilb; Slope aspect N: North, S: South, SE: Southeast

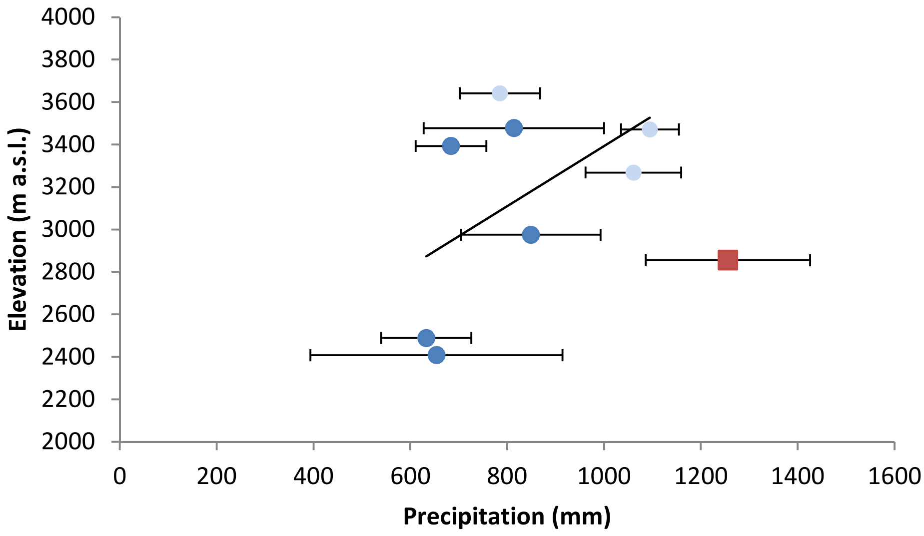

Figure 8.7 Vertical distribution of average annual rainfall (2012-2014) (R) with increasing elevation (A). Ferrah Amba stations in dark blue, Lib Amba stations in light blue and Debark station in red (excluded from the regression).

8.3.3 Air temperature

The air temperature was relatively stable throughout the year, while the daily temperature fluctuation was relatively high (Figure 8.4). The difference between the average maximum and minimum temperature is 10°C or more. The seasonal variation in air temperature is higher in the lower stations. The difference between the average coldest month and the warmest month is 5.7°C in Maychew whereas this is only 3.3°C in Godagudi (Figure 8.8). The inter-annual variability of the mean minimum and maximum air temperature (expressed by the standard deviation) is also higher for the lower stations (Figure 8.8). The maximum temperature is more variable in the rain season, while the minimum temperature is more variable in the dry season. Maximum temperature in the lower station of Maychew peaks at the onset of the wet season in June. The diurnal difference between maximum and minimum temperature is also higher in the stations at lower elevations. Air temperature variability decreases with elevation. At the upper station of Godagudi the seasonal and inter-annual variation of minimum and maximum temperature is very small.

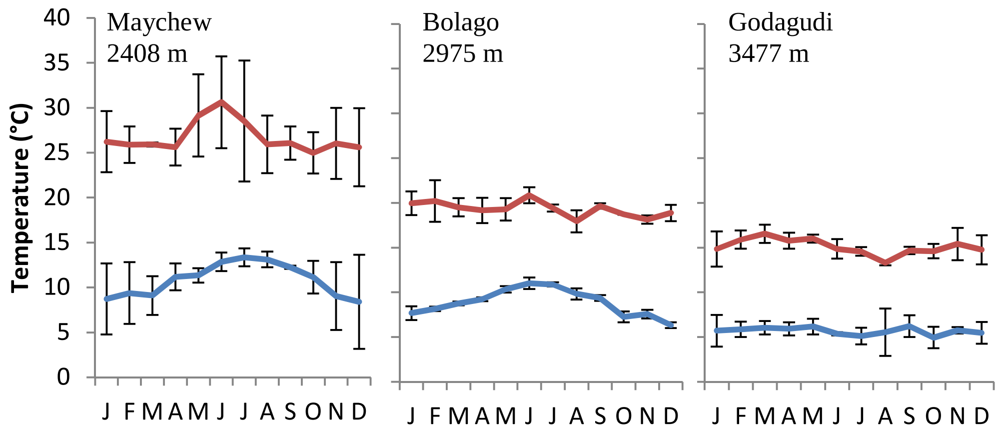

Figure 8.8 Mean monthly minimum (blue) and maximum (red) temperatures for three stations at Ferrah Amba with different elevations: (a) Maychew, (b) Bolago and (c) Godagudi.

The vertical distribution of air temperature is a key factor controlling the treeline elevation (Chapter 2; Harsch et al., 2009; Holtmeier, 2009; Körner, 1998). A linear regression was used to derive the environmental lapse rate for the average minimum, average and average maximum temperatures. Air temperature and elevation are strongly correlated (with an R^2 of 0.84, 0.88 and 0.86 for respectively minimum, average and maximum temperature). The temperature gradient with elevation is 0.72°C per 100 m for the average temperature, while the minimum temperature decreases slower with 0.50°C per 100 m and the maximum temperature faster with 0.95°C per 100 m (Figure 8.9). At higher elevations, the trendlines converge, confirming the observed lower variability with increasing elevations. The average temperature lapse rate in the rain season (0.81°C per 100 m) is higher in comparison to the dry season average lapse rate (0.63°C per 100 m).

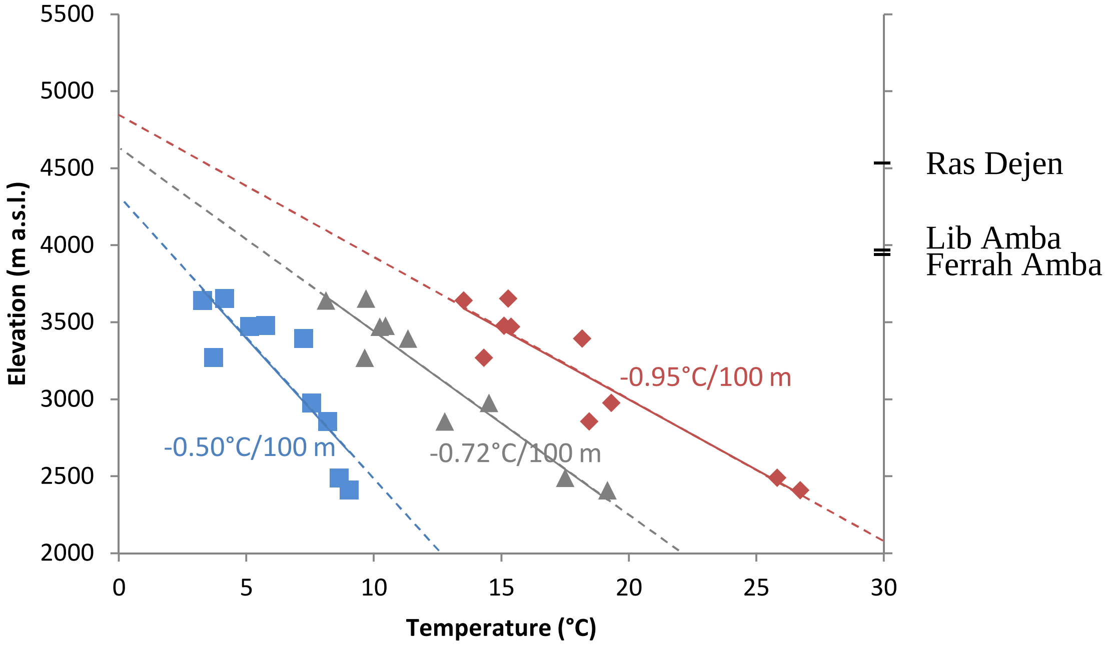

Figure 8.9 Vertical distribution of the minimum (blue), average (grey) and maximum (red) air temperature in the North Ethiopian mountains, with temperature gradients. The elevation of some mountain peaks is indicated.

8.3.4 Soil temperature

In total 28% of the soil temperature loggers failed, due to technical failures or loss. We recovered the data of 27 loggers that measured Ground Surface Temperature (GST) at -2 cm and 24 loggers for Soil Temperature (ST) at -12 cm, evenly distributed between Lib Amba and Ferrah Amba (Figure 8.10).

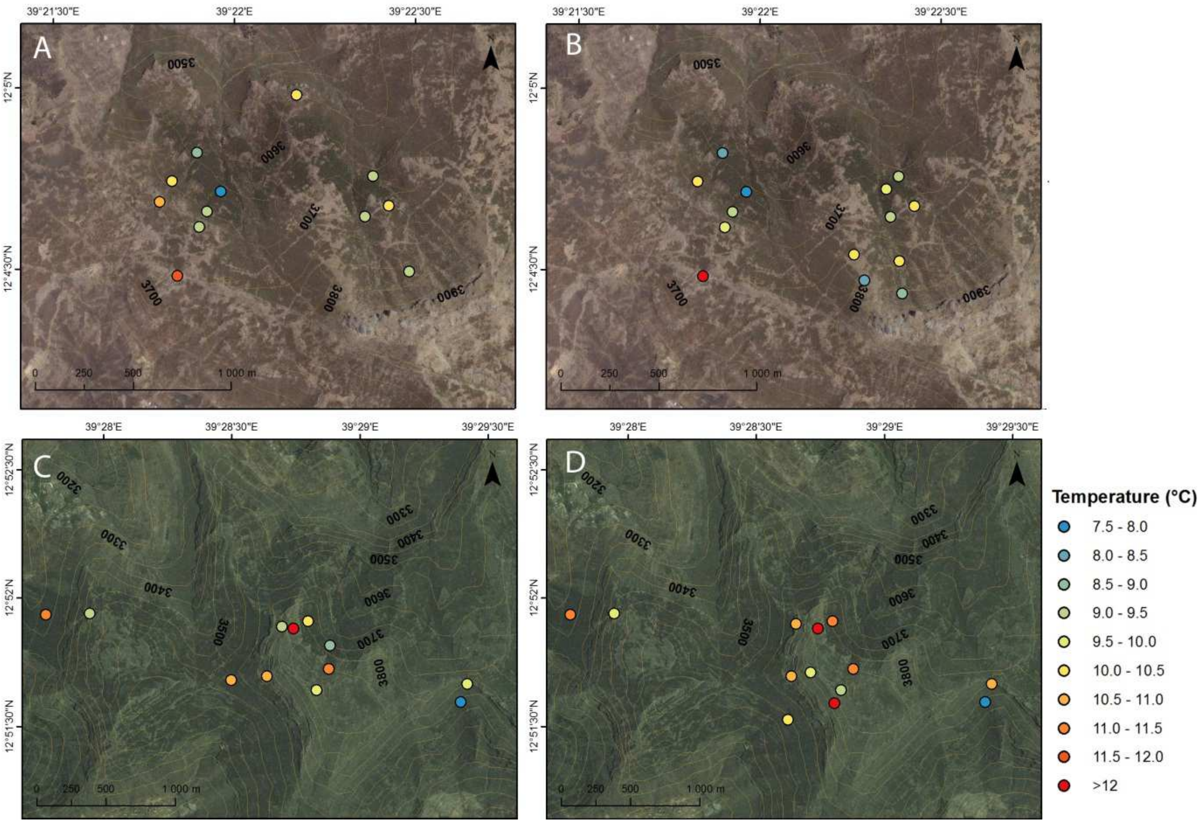

Figure 8.10 Distribution of the temperature loggers with indication of average temperature: (A) ST Lib Amba, (B) GST Lib Amba, (C) ST Ferrah Amba and (D) GST Ferrah Amba

The seasonal variation of the GST and ST is given in Figure 8.11, for Lib Amba and Ferrah Amba respectively. In Lib Amba the soil temperature (GST and ST) is highest in March and in June at the beginning of the rain season when the noon sun is overhead (Figure 8.11). Between March, and June there is a dip in the soil temperature associated with increased cloud cover during the azmera rain season. This azmera effect is missing in Ferrah Amba, the soil temperature peaks in April and decreases afterwards. In Lib Amba the annual variability of the soil temperature (GST and ST) is higher, i.e. 2.6°C higher for the GST and 1.5°C higher for the ST. In both study areas, the variation of the ST is lower in comparison to the GST. During periods of reduced GST, the ST rises higher than the GST. This indicates that the ST is buffered by the soil from fluctuations in surface heating.

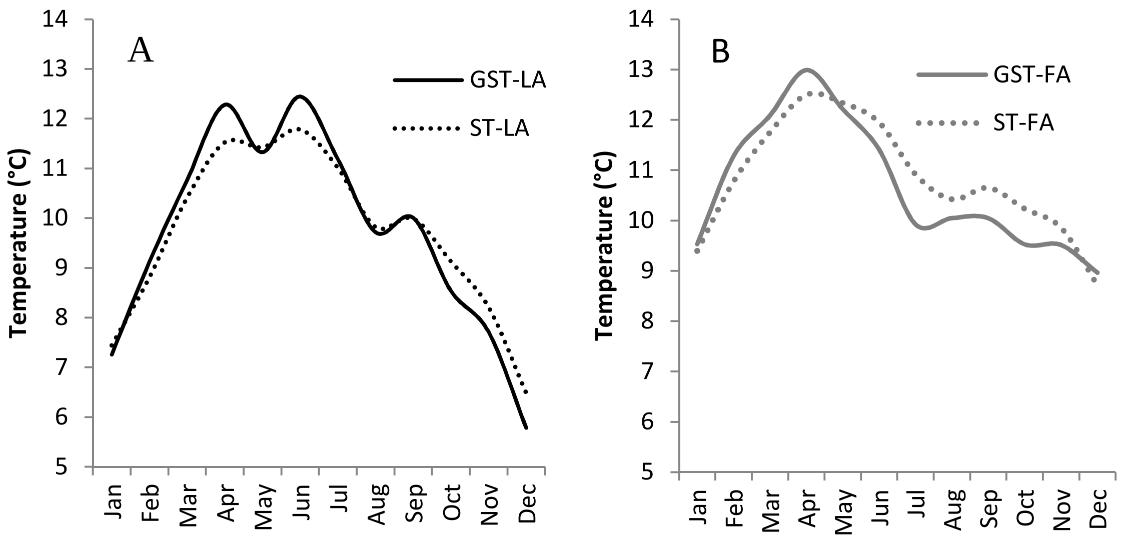

Figure 8.11 Seasonal variation of soil temperature (GST and ST) for (A) Lib Amba 25 loggers located between 3600 – 3900 m and (B) Ferrah Amba 26 loggers located between 3300 – 3900 m

The diurnal and seasonal fluctuation of the ST in Lib Amba is shown in a thermo-isopleth diagram (Figure 8.12). For this thermo-isopleth diagram the average of four non-forested loggers at the treeline elevation in Lib Amba (approx. 3700 m a.s.l.) are used. The seasonal differences in the soil temperature are more important than the diurnal differences. The coldest soil temperature is found at 10 am all year round, while the warmest soil temperature is found at 18 pm. The seasonal variation of the soil temperature at 10 am is 6°C and at 18 pm this is 7°C throughout the year. While the daily temperature, varies with 3.5°C in June and only 2°C in December. Overall, the soil temperature is almost 60% of the time above 10°C or more.

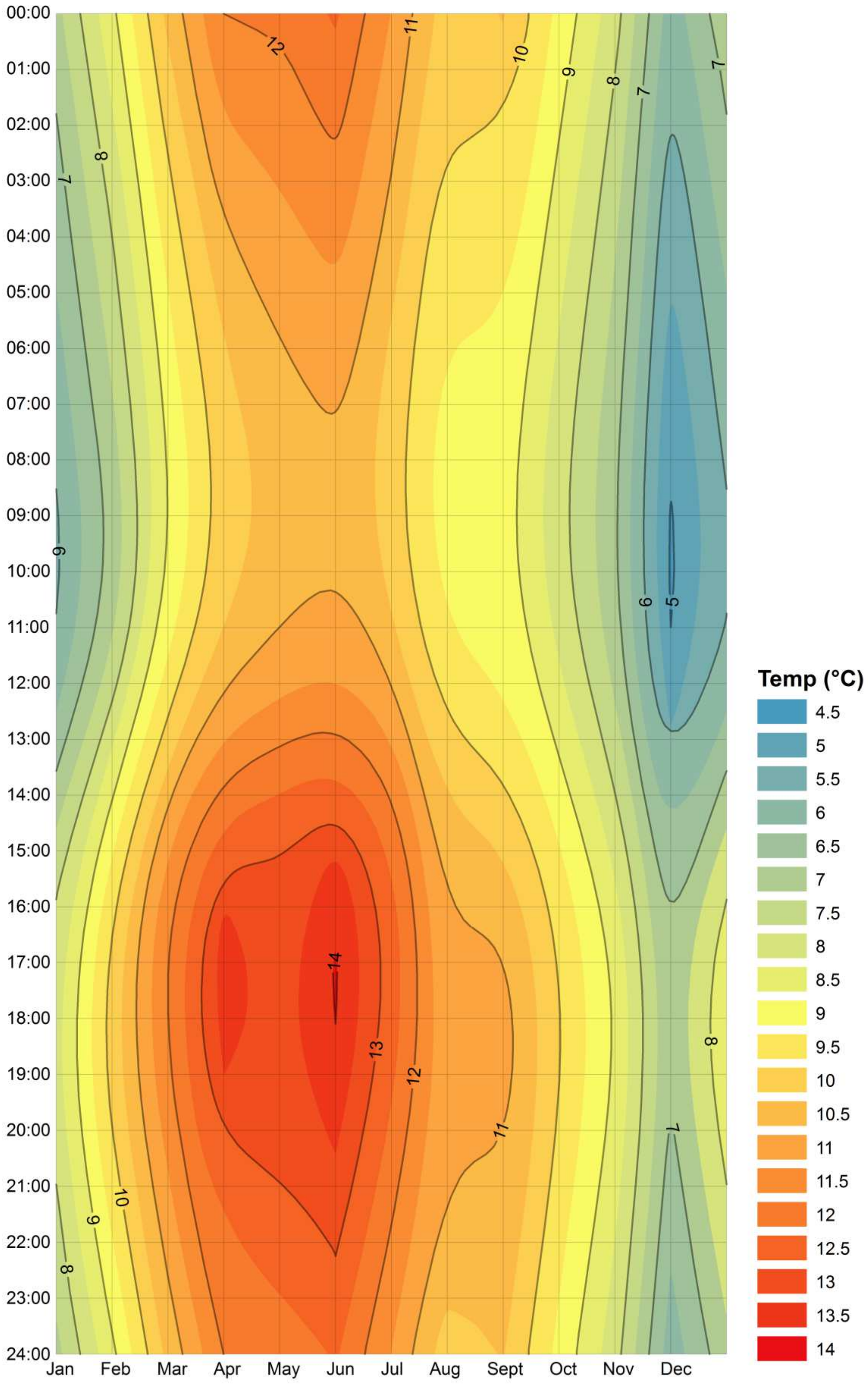

Figure 8.12 Thermo-isopleth diagram of soil temperature (-12 cm) at the treeline elevation (approx. 3700 m a.s.l.) in Lib Amba

Vegetation cover and forest cover in particular have a strong effect on the soil temperature. The average difference between forested and non-forested areas in Lib Amba is 1.8°C for ST and 1.6°C for GST (Figure 8.13). In particular, the increased surface heating in April-June is less expressed in the areas under forest.

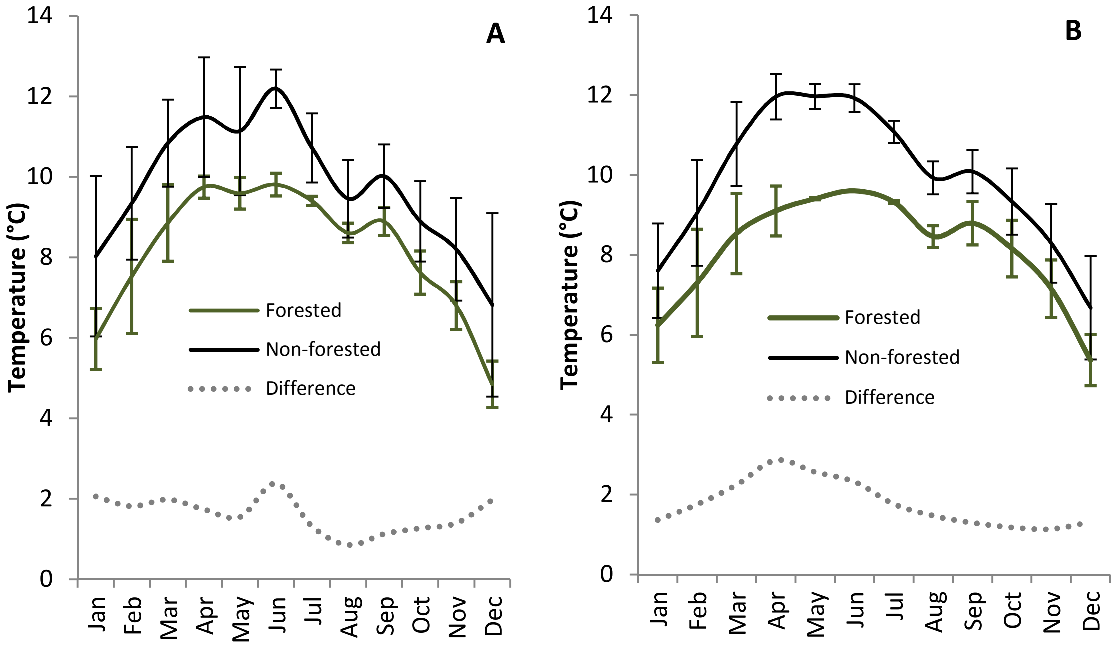

Figure 8.13 A comparison of soil temperature between forested and non-forested areas for (A) GST Lib Amba and (B) ST Lib Amba. Only soil temperature loggers with a similar exposition and slope are used. GST: 2 forest and 3 non-forest loggers; ST: 2 forest and 4 non-forest loggers.

The spatial distribution of soil temperature in the study areas is complex and unlike air temperature, it does not show a simple decreasing trend with elevation (R^2 <0.03 for both GST and ST). Therefore, the additional parameters slope, aspect and vegetation buffer capacity were investigated. A coefficient for the received radiation in function of the position of the loggers on the slope and the incident angle of the sun is based on an adaptation of the equation for the hydrological rainfall (Fourcade, 1942).

$$E_{Corr} = 1 + \tan\alpha \times \tan\beta \times \cos(z\alpha - z\beta) \qquad (1)$$

Where: E_{corr} is a correction factor for the energy received at a given location; α is the local inclination of the ground surface at that point relative to the horizontal (i.e. slope gradient in deg.); β is the inclination of the sun relative to the vertical; zα is the aspect of the ground surface at that point (°); and zβ is the direction from which the radiation is received (°). The direction of the radiation is simplified by taking the position of the sun at noon. This correction factor for incoming radiation is significant in relation to average ST during winter in Lib Amba (Table 8.3, Figure 8.14).

Table 8.3 Strength of the relation between soil temperature (-12 cm) and incoming radiation for different periods of the year

Date	Beta-LA	Beta-FA	Z-beta (sun azimuth at noon)	R^2 (ST vs E_{corr}) LA	FA
21 March	12.35	13.16	148.5	0.08	0.05
21 June	-11.35	-10.57	172.12	0.003	0.22
21 September	12.75	13.50	161.71	0.0001	0.20
21 December	35.52	36.30	26.67	0.73	0.01
Summer	*	*	*	0.23	0.21
Winter	**	**	**	0.72	0.003

* 21 June; ** 21 December

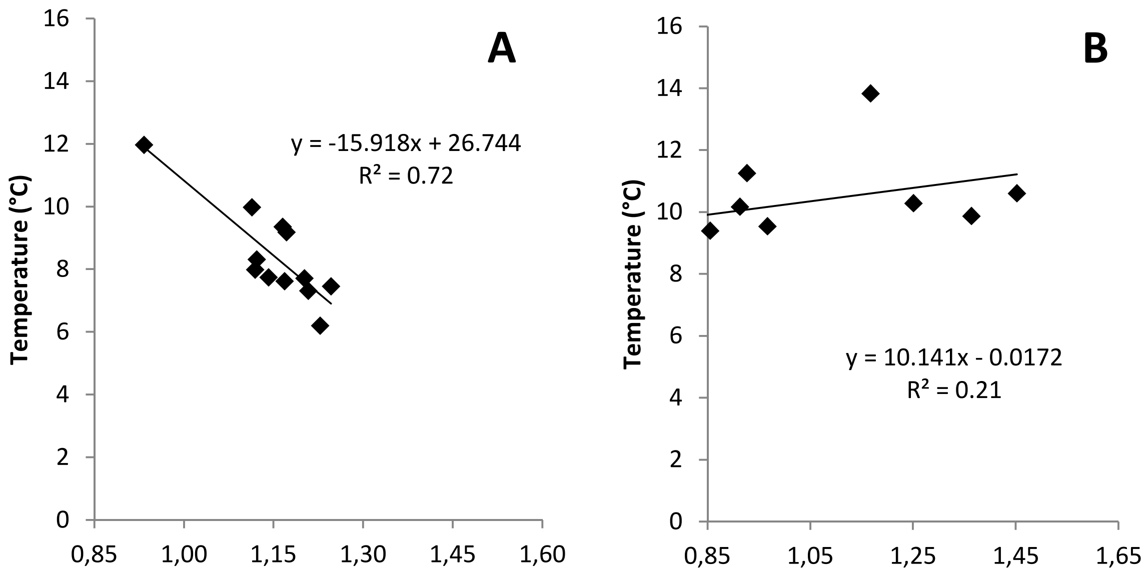

Figure 8.14 Correction factor for incoming radiation versus mean ST for (A) winter in Lib Amba and (B) summer in Ferrah Amba.

Beside incoming radiation, vegetation also plays a critical role as shown by the differences in ST and GST between forested and non-forested areas. The mean soil temperature (GST and ST) decreases with increasing vegetation cover (Figure 8.15). This relation is stronger under higher vegetation cover as observed in Lib Amba (GST R^2:0.44 and ST R^2: 0.78).

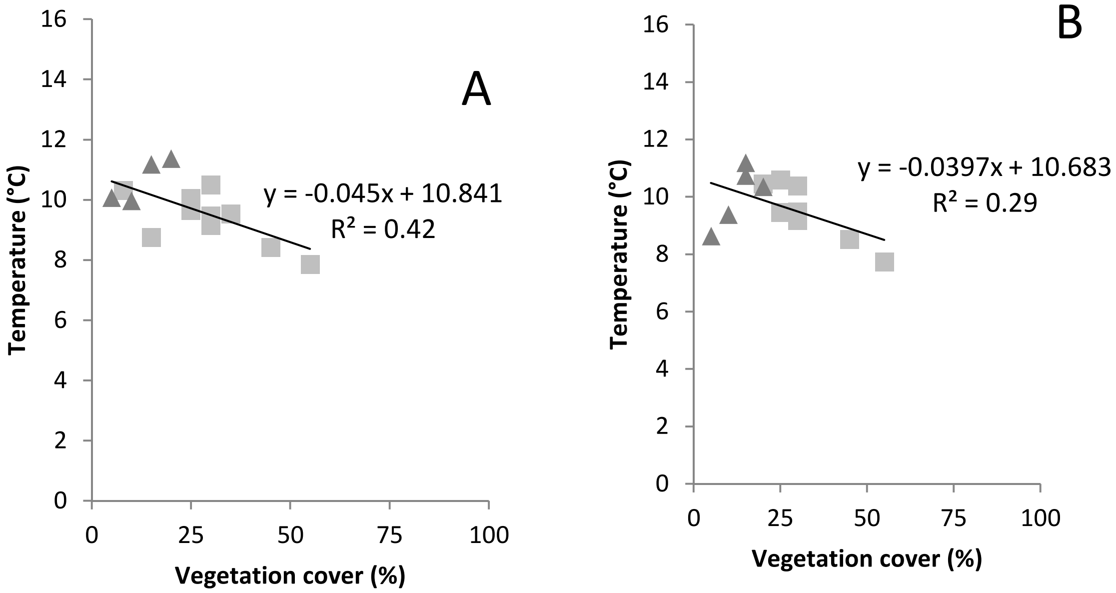

Figure 8.15 Effect of vegetation cover on mean soil temperature (A) GST and (B) ST. The trendline and equation are given for all data. Lib Amba points are squares and Ferrah Amba points are triangles.

These explanatory variables for the spatial distribution of soil temperature, incoming radiation and vegetation cover, in combination with altitude are evaluated in a multiple linear regression model. The spatial variation of ST in Lib Amba is for 70% explained by the radiation correction factor in the winter and for 60% by the vegetation cover in the summer, whereas elevation is not significant as explaining factor (eq. 2 and 3). In Ferrah Amba none of the variables are significant in explaining the spatial distribution of the soil temperature (GST and ST).

$$ST_{summer} = 1122.046 - 3.712 \times V \qquad (R^2: 0.59; P<0.05) \qquad (2)$$

$$ST_{winter} = 2635.079 - 15.58 \times E_{corr}^{winter} \qquad (R^2: 0.70; P<0.05) \qquad (3)$$

With: ST the soil temperature at -12 cm, E_{corr} a correction for the energy received and V the percentage vegetation cover.

In Table 8.4, the average soil temperature (-12 cm) in Lib Amba is given for three different belts of the afro-alpine vegetation: the *Erica* forest, the treeline and the afro-alpine grassland. As stated earlier, the average temperature is lower in the forest. Above the forest the average soil temperature decreases with elevation in Lib Amba (with 0.5°C between the treeline at 3700 m and the grasslands at 3800 m).

Table 8.4 Soil temperature (-12 cm) in Lib Amba for three vegetation belts

	Day and night (°C)*	Altitude (m a.s.l.)	Loggers
Erica forest	8.12 ± 1.5	3600	2
Treeline	9.77 ± 2.4	3700	4
Afro-alpine grassland	9.28 ± 2.3	3800	2

* Soil temperature (-12 cm)

8.4 Discussion

8.4.1 Mountain microclimate

Altitude is the most fundamental characteristic of mountain climates, because atmospheric density, pressure and temperature decrease with height in the troposphere. Due to the lower heat capacity of the atmosphere at higher elevations, the diurnal and annual range of temperature decreases (Beniston, 2006). This is also observed in the study area. The seasonal effect and the inter-monthly and diurnal variability of the air temperature decreases with elevation (Figure 8.9). The lower average temperature lapse rate in the dry season (0.63°C per 100 m) is caused by radiative cooling during the Northern hemisphere winter (Kattel et al., 2013). Decreased soil temperatures from May to September are the result of the increased cloud cover during the rain season, which reduces surface heating. In addition, decreasing temperatures remove heat from the soil, further reducing the soil temperature. By November the southward movement of the noon sun reduces surfaces heating (Geiger et al., 2003). The seasonal variability of the soil temperature indicates a strong warming in the summer due to the northern aspect of the slope (Figure 8.12). A similar seasonal trend of the soil temperature is observed in Pico de Orizaba in Mexico (Körner, 2012). The soil temperature is indicated to be lower under forested areas, a difference of 1.8°C for the ST and 1.6°C for the GST is found in the study area. This vegetation effect on soil temperature is also observed in the tropical Andes by Bader et al. (2007). This difference is related to the radiation regime. On clear days the unforested areas strongly warm during the day and strongly cool during the night due to radiation (Bader et al., 2007). Whereas closed tree canopies at the forest create cooler soils with a reduced soil heat flux due to shading effects which impair root activity (Bendix and Rafiqpoor, 2001). The temperature difference between tree-sheltered and non-shaded surfaces can be up to 4°C (Miehe and Miehe, 1994). This interaction between vegetation and its environment causes a positive feedback mechanism, sheltering tree seedlings against diurnal soil temperature variability (Bader et al., 2007). The complex behavior of the soil temperature is potentially due to the narrow altitudinal range considered in this study. In addition, the complex topography of Ferrah Amba further disturbs the spatial soil temperature patterns.

Higher rainfall amounts are observed in Debark in comparison to rainfall in Lib Amba and Ferrah Amba. Likewise, rainfall amounts in the Simen Mountains (1515 mm year^{-1} at 3600 m in Gich) (Hurni & Stähli 1982) are higher than in Lib Amba (1028 mm year^{-1}) and Ferrah Amba (733 mm year^{-1}). The tendency of increasing rainfall with elevation between 2400 and 3600 m a.s.l., although not significant, is in agreement with the description by Hurni & Stähli (1982) for the Simen Mts. Enhanced orographic rainfall is potentially responsible for an increase in rainfall with elevation, however other parameters are proven more important than elevation in explaining the spatial distribution of rainfall. This absence of a significant relation with elevation is also confirmed by the observations of Chapter 7 for Tigray. Spatial variability of rainfall in northeastern Ethiopia, is mainly determined by the northwards movement of the ITCZ (Ogallo, 1989). Lib Amba is located south of Ferrah Amba and subsequently receives more rainfall due to the movement of the ITCZ. However, the Simen Mountains are located more northwards and still receive more total annual rainfall. This is due to the 1000-meter high escarpment with rainfall advectively brought by trade winds over the escarpment edge (Hurni and Stähli, 1982). Unreliable rainfall patterns in the azmera season are associated with unstable moist air masses irregularly carried by eastern winds over the Indian Ocean to eastern Ethiopia (Chapter 7).

8.4.2 Impact of the mountain microclimate on the treeline

The vertical distribution of climate factors with elevation forms an important determinant for the limit of tree growth (Smith et al., 2009). For this reason, the observed and expected trends of air temperature and rainfall with altitude are combined in one graph. The effect of altitude on the soil temperature is influenced by vegetation cover and incoming radiation. If all data is considered, there is no significant link with elevation for the observations. But if only the data above the forest in Lib Amba is considered, average soil temperature tends to decrease with elevation (0.5°C between 3700 and 3800 m). At the treeline elevation, soil temperatures are not expected to limit tree growth in the study area, since average soil temperatures (ST) of more than 9°C are observed. It is only at approx. 4100 m that the minimum mean soil temperature in the root zone (at -10 cm) of 6.7°C ± 0.8°C (Hoch and Körner, 2003) is reached (Figure 8.16), based on the 0.5°C per 100 m trend as observed in Lib Amba. However, more soil temperature data, along a much wider altitudinal range, is needed to validate this hypothetical trend.

The use of average soil temperatures for identifying the tree growth limit is questioned by Bader et al. (2007), because soil temperature is higher in the grasslands above the forest. This is in line with the results of this study and also observed in several other tropical studies (Bader et al., 2007; Bendix and Rafiqpoor, 2001; Miehe and Miehe, 1994). High daily temperature differences, caused by low night temperatures and followed by strong solar radiation during the day, are indicated as a potential explanatory variable for the treeline (Bader et al., 2007). These diurnal differences are higher above the forest at higher elevations, which indicates the importance of the positive feedback mechanism of the forest. However, treeline elevations in the Simen Mts. up to 4000 m a.s.l. (Chapter 6) indicate that this effect is not yet limiting in the study area.

Annual precipitation tends to rise with altitude, although this relation is not significant. The effect of increased rainfall on tree growth is potentially twofold. A positive relation between tree growth and increased precipitation is observed in the subtropical mountains of Northwestern Argentina (Morales et al., 2004). In this study water stress impedes tree growth, this is in line with findings by Körner (2012) and Wieser and Tausz (2007). But, this is in contrast with the negative effect of increasing rainfall and cloudiness due to reduced solar radiation described by Smith & Young (1987). A negative relation between rainfall and tree growth is observed in the humid mountain rainforests of southern Ecuador by Bräuning et al. (2009). At the highest altitude, near the peak, rainfall is expected to decrease again as observed in the Bale Mountains (Miehe and Miehe, 1994). Such drier conditions at the summit elevation are also observed in Lib Amba Mt. Global climate models predict wetter conditions for East Africa under global warming (Chandler et al., 2005). Increased rainfall amounts are not expected to limit tree growth in Ferrah Amba and Lib Amba, because higher treeline elevations are observed in the Simen Mountains under wetter conditions.

Air temperature is, in contrast to soil temperature, strongly related with altitude. The mean air temperature decreases with 0.72°C per 100 m in the study area. The expected treeline elevation corresponds with a mean air temperature of 5°C in the tropics. According to the observed environmental lapse rate of air temperature in the study area, this mean temperature of 5°C corresponds with a potential treeline elevation at approximately 4100 m a.s.l. This corresponds with the lower limit of the potential climatic treeline based on the observed trend of soil temperature with elevation. The current treeline at 3700 m a.s.l. is thus located 400 m below its potential climatic limit (Figure 8.16). This potential theoretical treeline limit can be expected for tree growth in the Simen Mountains. Evidence of a treeline uplift in the Simen Mts. up to 4000 m a.s.l. is given by Hurni (2005) and in Chapter 6. But a similar treeline rise is not expected for the mountains of Ferrah Amba and Lib Amba because they range slightly below 4000 m a.s.l. and because the summit effect depresses the treeline near the summit. The summit effect is the result of strong winds and loss of substrate at the summit (Körner, 2012). In temperate regions, forceful westerlies at high elevations can depress the treeline with several hundred meters (Körner, 2012). However, lower wind speeds in the tropics strongly limit the summit effect. These effects alone cannot explain the 400 m difference with the potential climatic limit.

According to the National Adaptation Plan of Action (NAPA) of Ethiopia, temperature increased by 0.37°C per decade in the period 1951-2005 (Tadege, 2007). Climate projections for Ethiopia by the Intergovernmental Panel on Climate Change project a further temperature rise (compared to the 1961-1990 normal) between 0.9-1.1°C by 2030 and 2.7-3.4°C by 2080 (IPCC, 2007). The potential effect of an air temperature increase of 1°C on the treeline elevation is projected in Figure 8.16 and corresponds with an increase in altitude by approximately 150 m.

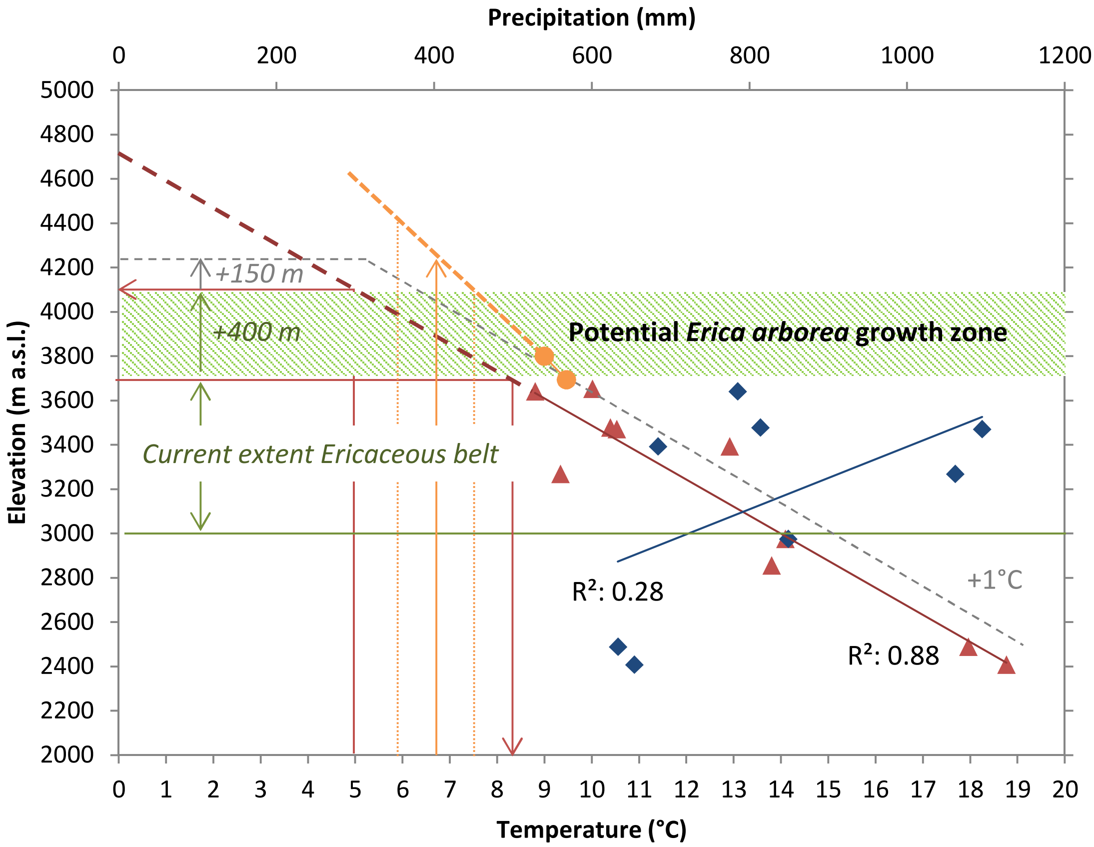

Figure 8.16 Altitudinal gradient of air temperature (red), average soil temperature at 100 m interval (orange) and rainfall (blue). With indication of the potential treeline limit corresponding with a mean air temperature of 5°C (red arrows) and a mean soil temperature of 6.7±0.8°C (orange arrow and lines). The potential effect of an increase of the air temperature with 1°C at the treeline elevation is indicated in grey.

8.5 Conclusion

Climate is a key factor regulating tree growth by setting limitations for tree survival, for species composition and stand characteristics. Three key characteristics of mountain climates were studied in the North Ethiopian highlands, i.e. rainfall variability, air and soil temperature. Rainfall follows a bimodal rainfall pattern with an unreliable small rain season preceding the main rain season. The total annual rainfall is higher for the southern highlands. There is no significant relation of annual rainfall with elevation, while in contrast air temperature is strongly related to altitude. The seasonal variation, inter-monthly variation and diurnal differences of air temperature decrease with elevation. The average environmental lapse rate of air temperature is 0.72°C per 100 m. Soil temperature peaks in March-June when the noon sun is overhead and decreases afterwards with increased cloud cover in the rain season. The diurnal variability of the soil temperature is lower than the seasonal difference. The coldest soil temperature is found at 10 am and the warmest at 18 pm. The spatial distribution of the soil temperature is partly explained by the incoming radiation, the vegetation cover and the elevation for Lib Amba Mt. The buffer effect of forest cover is in particular important, the soil temperature at -12 cm for areas under forest are on average 1.8°C colder. There is no significant relation between soil temperature and altitude. However, the positive feedback mechanism of the forest is important in sheltering against high diurnal fluctuations of the soil temperature at higher elevations. The current treeline is depressed below its potential climatic limit by 400 m.

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Chapter 9 The response of *Erica arborea* tree growth to climate variability in the afro-alpine tropical highlands of North Ethiopia

This chapter is based on:

Jacob, M., De Ridder, M., Vandenabeele, M., Frankl, A., Asfaha, T., Nyssen, J., Beeckman, H. (2015). Are the high altitude treelines sensitive to climate variability? A dendroclimatological study in the North Ethiopian highlands. Trees, in preparation.

Abstract

The important ecosystem services of the high altitude tropical afro-alpine *Erica arborea* forests are under increasing environmental and human pressure. The *Erica* treeline ecotone in the Ethiopian highlands forms a temperature-responsive vegetation boundary, potentially affected by climate change. The cambium of ten *Erica arborea* trees in Lib Amba Mt. in the North Ethiopian highlands was marked in 2012 and corresponding tree disks sampled after 498 days. Microphotographs of these cambial marks confirmed the formation of annual growth rings (0.76±0.24 mm) with higher vessel density in earlywood and radially flattened fibers in the last layers of the latewood. In-continuum measurements of vessel size and density on microphotographs indicated the formation of Inter-annual Density Fluctuations (IADFs) related with early rainfall in March-May. The same stem disks and 40 increment cores were used for detailed tree-ring analyses: a tree-ring chronology with 18 trees spanning from 1966 to 2014 could be derived. A significant ($p < 0.1$) positive correlation with minimum temperature in the growing season (August) and a negative correlation with minimum temperature in the azmera season (March) were proven to be the most important climate factors regulating tree growth of *Erica* trees in the afro-alpine forest. The existence of annual tree rings and the proven potential for chronology building encourages further tree-ring analyses of *Erica arborea* in the afro-alpine tropical highlands in order to link it with climate variability and climate change.

Keywords: *Erica arborea*; Cambial Marks; Dendrochronology; IADFs; Precipitation; Minimum temperature; Vessel characteristics

9.1 Introduction

Tree rings can contain valuable information on the long-term tree memory and forest history, as influenced by biotic and environmental factors (Rossi and Deslauriers, 2007). This linkage between tree rings and environmental factors (e.g., temperature, precipitation) provides a good opportunity to estimate retrospectively environmental dynamics (De Micco et al., 2014), which may help to understand forest dynamics in relationship to their controls.

Dendrochronological studies are recently increasing beyond the borders of temperate and boreal regions (Wils et al., 2010b). Annual growth rings have been identified on a number of species in the tropics and have partly ended a lively debate about the existence of annual tree rings in the tropical regions (Worbes, 2002; Trouet et al., 2010; De Ridder et al., 2013). Tree rings in the temperate and boreal zone are typically formed by intra-annual temperature and light fluctuations. Because temperature variations in the tropics are relatively small, tree rings in these regions are potentially formed by intra-annual rainfall variability (Worbes, 2002). However, less strictly defined cycles in water availability can cause non-annual tree rings (Wils et al., 2010b). This still causes major challenges for dendrochronological studies in the dry tropics (Wils et al., 2010b). Within the European context, similar challenges are encountered in the Mediterranean region were summer drought and winter rain patterns are less reliable (Cherubini et al., 2003).

Due to the occurrence of indistinct growth rings and ring anomalies, tree-ring studies in the tropics and especially in Africa south of the Sahara remain scarce (Worbes, 2002). However, in recent decades reliable climate-sensitive tree-ring chronologies have been developed for western Africa (Worbes et al., 2003; Schöngart et al., 2006) and Ethiopia (Couralet et al., 2005; Gebrekirstos et al., 2008) and drought-sensitive chronologies were indicated in Zambia (Trouet et al., 2006), Namibia (Fichtler et al., 2004) and Zimbabwe (Therrell et al., 2006).

In the semi-arid savanna lowlands of Ethiopia, a ring-width chronology of 68 years was developed based on *Acacia* tree-ring measurements (Gebrekirstos et al., 2008). This chronology has strong positive correlations with precipitation data, which indicates the annual formation of tree rings (Stahle, 1999). Still, tree-ring formation is proven complex as parts of the stem disks and wood increment cores had to be discarded due to missing rings (Gebrekirstos et al., 2008). Tree-ring chronologies of *Juniperus procera* in the Ethiopian highlands were established with varying results (Wils et al., 2010a). The annual tree rings are disturbed due to high inter- and intra-annual rainfall variability. Four typical tree-ring types have been identified by Wils et al. (2010a): indistinct rings, multiple rings, annual rings and multiple missing rings dependent on the rainfall regime and tree sensitivity to water availability.

At present, little is known about tree-ring formation in the afro-alpine *Erica arborea* forests of Ethiopia, although these mountain forests provide important ecosystem services (Miehe and Miehe, 1994; Aerts et al., 2002; Nyssen et al., 2004). The University of East Anglia did a dendrochronological study of *Erica arborea* tree samples in 1996, with as conclusion that *Erica* trees in the North Ethiopian highlands only have a limited potential for dendrochronological research (Conway et al., 1997). However, *Erica arborea* tree samples show a moderately good visibility of growth boundaries (Kaeppeli, 1998). Therefore, Kaeppeli (1998) conducted a detailed dendrochronolgical analysis of *Erica arborea* trees in the North Ethiopian highlands and concluded that distinctness of the *Erica arborea* tree-ring boundaries varied within the tree and between individual trees. There were trees with high probability of annual tree-ring formation, but there were also indistinct boundaries or extremely small tree rings (Kaeppeli, 1998). The hypothesis of Kaeppeli (1998) is that rainfall outside the rain season can be held responsible for Inter-Annual Density Fluctuations (IADFs) (since dormancy is drought induced). Age determination is therefore difficult, but approximate ages can be derived which are sufficient to study treeline shift (Kaeppeli, 1998). Treeline shift was studied by Paulsen et al. (2000) by measuring tree height and tree age with increasing elevation and found that the potential of *Erica arborea* for dendroclimatology is limited, due to eccentric growth, partly indistinct ring boundaries and high human impact. Similar difficulties were found in *Erica* shrub tree-ring studies in the Mediterranean regions (Gea-Izquierdo et al., 2013). *Erica arborea* shrubs in the Mediterranean have proven to form IADFs in response to site-specific water stress (Battipaglia et al., 2014). The complex tree-growth pattern of *Erica* trees at the treeline ecotone in the North Ethiopian highlands forms the subject of this paper. The aim is to gain improved understanding of tree growth of *Erica arborea* trees in the North Ethiopian highlands; i.e. (i) understanding tree-ring formation and the link with climate variables, (ii) understanding the relation between tree growth, the presence and origin of IADFs and climate and (iii) deriving the forest gradient of tree height with elevation.

9.2 Materials and methods

9.2.1 Study area

To meet our objectives, stem disks and wood increment cores of 30 trees were sampled in the North Ethiopian highlands. *Erica arborea* wood samples were collected from two forests, i.e. Lib Amba Mountain of the Abune Yosef Mountain range (12°04’N, 39°22’E, 3993 m a.s.l.) and Ferrah Amba Mountain (12°52’N, 39°30’E, 3939 m a.s.l.). The North

Ethiopian highlands are the result of epeirogenic Tertiary uplift 45 million years ago, accompanied with successive lava flows, which formed near-horizontal Tertiary basalt layers (Hendrickx et al., 2015). These stratified basalt series are locally more than 2000 m thick and cover the formations of the Mesozoic sandstone and limestone, and Palaeozoic and Precambriam basement rocks (Bussert, 2010). Due to its volcanic history, inactive volcanic plugs and structural relief, forming steep escarpments characterize the study area (Chapter 3). The dominant soil type of the high altitude soils are well developed Andosols (Wesche et al., 2000). The study sites are 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 and Nile Basin in the west (Figure 9.1). The two mountains were selected because both are ranging above the present treeline elevation (approx. 3700 m).

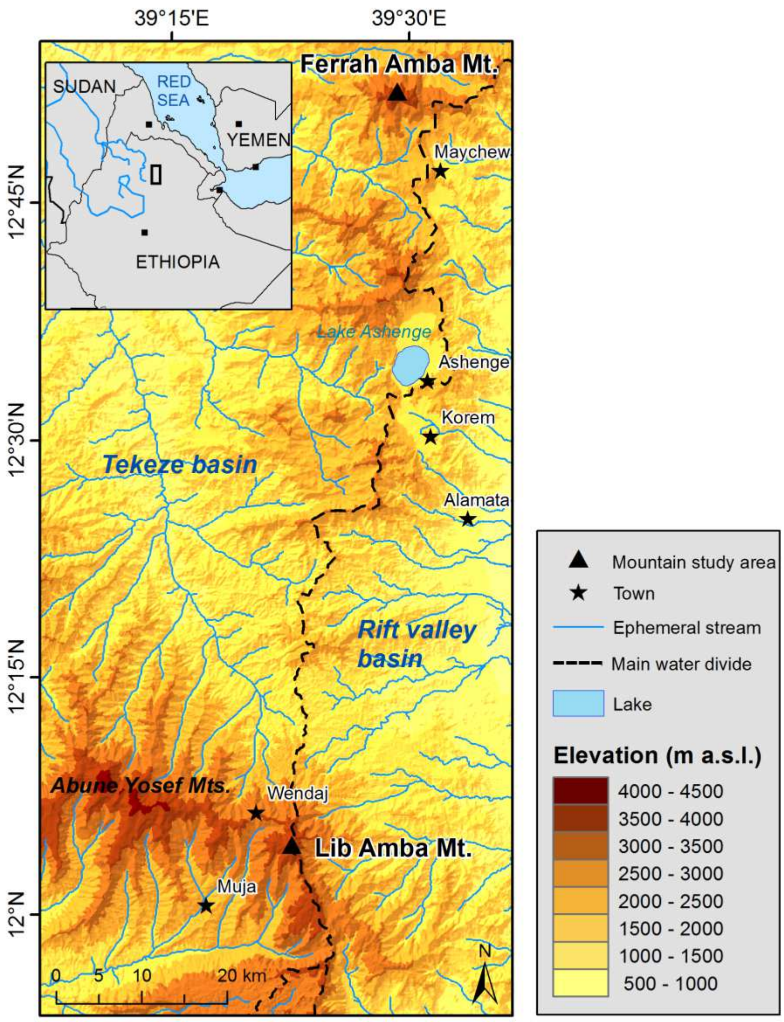

Figure 9.1 Location of the study area

Rainfall in the study area shows a bimodal rainfall distribution with an unreliable short 'azmera' rain season (March-May) preceding the main 'kiremt' rain season (June-September) (Figure 9.2). The mean annual precipitation varies with elevation and is approximately 862 mm near the afro-alpine belt in Lib Amba (Chapter 8). Mean air temperature is nearly constant throughout the year (8.8±0.7°C), whereas the diurnal temperature variation is high (9.5±1°C). This climate data were obtained in a meteorological station installed near the upper forest in Lib Amba (2012-2014) (Chapter 8).

The vegetation belts encountered in the study area, are the same belts as mapped in the Simen Mts. by Hurni and Stähli (1982), but at different vegetation growth limits, related to local biophysical constraints. These vegetation belts are: the *Acacia* upper limit at ca. 2730 m, the *Hagenia*, *Juniperus* and *Olea* montane forest limit at ca. 3200 m, the *Erica arborea* treeline limit at ca. 3700 m and the upper grass-steppe vegetation limit at ca. 4225 m. The afro-alpine high altitude forest is dominated by *Erica arborea*, which forms the upper treeline ecotone (Wesche et al., 2000).

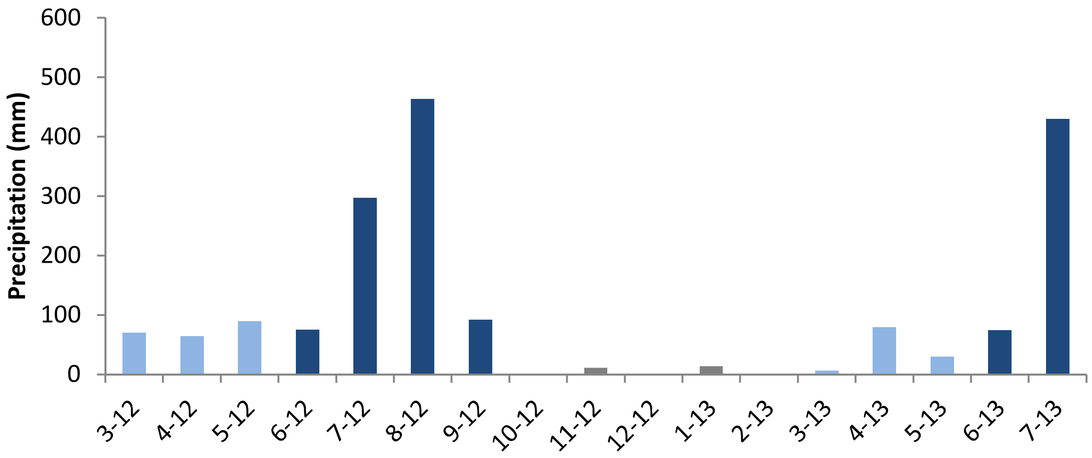

Figure 9.2 Rainfall patterns between March 2012 and July 2013 with in light blue the azmera season, in dark blue the kiremt season and in grey rainfall during the dry season. The period plotted corresponds with the period between cambial marking and sampling of the stem disks.

9.2.2 Data collection

At both sites, five trees received a cambial mark in early March 2012. Such cambial marks are mechanical injuries of the cambium that cause a wound response in the tree, which acts as a time marker (Mariaux, 1967). In each site, the marked stem disks were sampled at the end of July 2013. These stem disks were air-dried and transverse sections were sanded (up to 1200 grit) until the tree rings were completely visible. In addition, more samples were collected in the two study areas in November 2014 using an increment corer along 8 main transects crossing the mountain forest upslope with a 20 m elevation interval (Figure 9.3). At each interval level, five trees were sampled with two cores each. The trees are cored as close to the ground level as possible, while still allowing room for handling the increment borer, in order to require maximum tree ages (Grissino-Mayer, 2003) (Figure 9.4). For each sampled tree, tree diameter and height were measured. Since tree height is relatively low (less than 5 m), heights were directly measured using a pole. In total, more than 400 tree cores were collected. All *Erica arborea* samples are stored in the Xylarium of the Royal Museum for Central Africa (Tervuren Wood Collection, accession numbers stem disks: Tw64881-64890; increment cores: numbers not yet assigned), Tervuren, Belgium. In this paper, the analysis is based on the cambial marked stem disks and the increment core data of one complete transect.

Figure 9.3 Wood sample collection using an increment borer in Lib Amba Mt. (A, B) tree coring and core extraction; (C) *Erica arborea* tree at Lib Amba Mt.

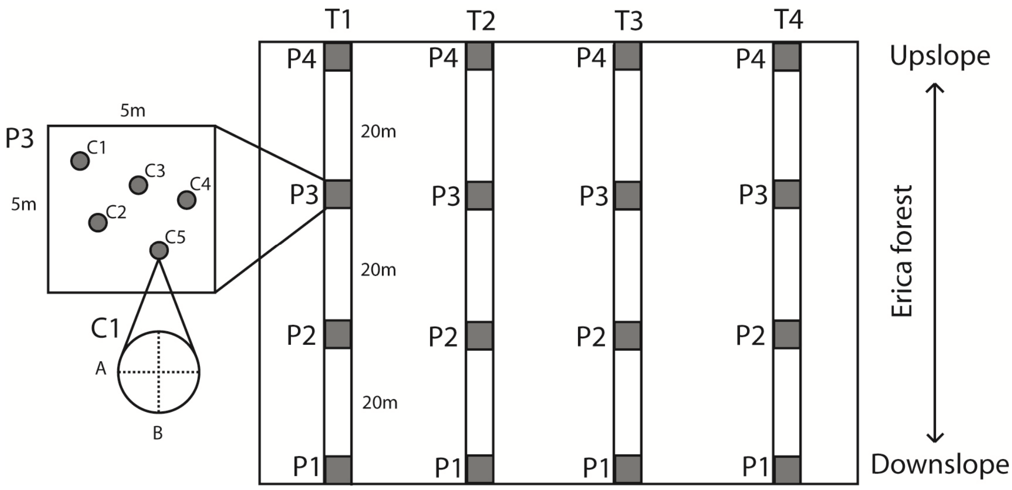

Figure 9.4 Schematic illustration of the sampling strategy. T stands for transect number (1-4); P stands for point number on the transect (1-4); C stands for the core number at the point (1-5); A and B stand for the two respective cores of one tree.

9.2.3 Dendrochronology

To derive a chronology, tree rings were marked on the ten stem disks and counted under a stereomicroscope along three radii. Ring widths were measured from scanned images (2400dpi) with ImageJ 1.47v (open-source software). In addition, tree-ring structures were derived from the increment cores. The cores were cut with a WSL core-microtome (Gärtner and Nievergelt, 2010) and the tree rings were counted under a stereomicroscope (Gärtner et al., 2015a). Moistening the increment cores with water helped to reveal the tree-ring structures. The tree-ring widths were measured using a Lintab measuring table. After the measurements, the tree-ring series were pairwise crossdated at the level of the individual tree to derive an average tree-ring width series per tree (TSAP Win software, Rinn, 2003). Subsequently, these individual tree-ring series were crossdated to find a tree growth chronology for all trees with a similar pattern (Douglass, 1941). The quality of the crossdated pairs were evaluated using three statistics: the Gleichläufigkeit (Glk), the t-value of Baille-Pilcher (tBP) and the cross-correlation (%) (Rinn, 2003). While crossdating, threshold limits of Glk > 60 and tBP > 2.0 were imposed (Trouet et al., 2010). Next to the mathematical variables for crossdating, visual control was another important condition for accepting or excluding certain trees from a chronology. A threshold of minimum four samples per year is set to guarantee a representative tree-ring chronology (De Ridder et al., 2014). The chronologies were tested for age trends using autocorrelation (AC) statistics (Rinn, 2003) and standardized using the five year moving average procedure of Baillie and Pilcher (1973). The Expressed Population Signal (EPS) indicates how well the sample chronology matches the theoretical population chronology; the threshold for a representative population signal is 0.85 (Wigley et al., 1984).

Table 9.1 Illustration of the cross-dating procedure for the *Erica arborea* stem disks: (Glk) Gleichläufigkeit and (tBP) t-value of Baille-Pilcher

Glk	Tw64887	Tw64886	Tw64888	Tw64890	Tw64884	Tw64889
Tw64887	x	66	65	63	64	71
Tw64886	x	X	64	73	64	64
Tw64888	x	x	x	63	64	71
Tw64890	x	x	x	x	67	68
Tw64884	x	x	x	x	x	67
Tw64889	x	x	x	x	x	x
tBP	Tw64887	Tw64886	Tw64888	Tw64890	Tw64884	Tw64889
Tw64887	x	1.7	2.1	0.3	1.5	0.3
Tw64886	x	X	1.6	0.4	0.4	0.6
Tw64888	x	x	x	1.8	1.2	1.7
Tw64890	x	x	x	x	0.9	1.4
Tw64884	x	x	x	x	x	0.2
Tw64889	x	x	x	x	x	x

9.2.4 Wood anatomical analysis

To study the wood anatomy of the tree rings, cubic samples of approximately 1 cm^3, containing the cambial marks, were cut from the stem disks of the two study areas. These *Erica arborea* cubes were softened in water at 80°C during two weeks, until microtome sections of 18µm thick could be sliced. The sections were stained with Safranin and Astra Blue, dehydrated with an ethanol series and mounted on permanent slides (Gärtner et al., 2015b). From these slides, microphotographs were made using Cell B software (Olympus TM). The microphotographs visualize in detail the number of tree rings and the amount of wood formed since the cambial marking (Verheyden et al., 2004). These microphotographs were used to identify IADFs according to the procedure of De Micco et al. (2014). In this procedure, the vessel size is measured in-continuum along the tree ring on 300-400 µm wide transects and plotted in a dispersion graph. This graph shows the variation in vessel size against the position of the vessel, expressed as percentage of ring width (De Micco et al., 2014).

9.2.5 Climate-Growth relationship

The climate growth relationship is subdivided in two parts: (1) the relationship between tree-ring formation, the presence of IADFs and rainfall variability on the one hand and (2) the relationship between the tree-ring chronology and climate variability on the other hand.

(i) Relation between the occurrence of IADFs and rainfall

Beside annual, kiremt and azmera rainfall, the dry spell indices from Seleshi and Camberlin (2005) were adapted to capture rainfall fluctuations. Two binary variables were constructed: rainfall dip and dry spell.

- The variable ‘rainfall dip’ is 1 if there is azmera rainfall with more than 100 mm followed by a dry spell of more than 10 days between the azmera and kiremt season and 0 in all other cases.

- The variable ‘dry spell’ is 1 if there is a dry spell of more than 20 days and 0 in all other cases.

The strength of the relations between IADF formation and rainfall was tested with an ‘N-1’ Chi-square test and a binary logistic regression in SPSS Statistics (IBM). The ‘N-1’ Chi-square test was used, because the amount of observations is smaller than 5 in three cells of the contingency table (Campbell, 2007). In addition, the phi coefficient was also calculated.

(ii) Dendroclimatology

To derive the climate effect on tree growth, the site chronology was correlated with monthly, seasonal and annual climate data (i.e. precipitation, minimum and maximum temperature). Because NMA station data for Maychew (1992-2013) and Lalibela (1997-2013) is spatially and temporarily limited, climate data was generated with KNMI climate explorer covering more than a century of climate data (1901-2013) (Trouet and Van Oldenborgh, 2013). The correlation between the local NMA stations and the climate explorer data is, however, very low for rainfall and minimal temperature (Pearson $r < 0.15$). Therefore, the climate explorer data (although the long record) is not used to match with tree growth. Beside temperature and precipitation effects, the combined Aridity Index (eq. 1) defined by de Martonne (1926) was used.

$$I_{DM} = \frac{P}{T + 10} \qquad (1)$$

With: I_{DM} the Martonne aridity index, P the annual mean precipitation in mm and T the annual mean air temperature in °C.

Relationships between climate variability and ring widths of the average tree-ring chronology were calculated with Pearson correlations (De Ridder et al., 2014).

9.2.6 Gradients of tree height with elevation

The gradient of tree height with increasing elevation is plotted in a scatterplot based on the transect tree height measurements. In addition, the relation between tree height and tree age is presented in a height-age curve for the afro-alpine *Erica arborea* forest. The strength of the relations is evaluated with a linear regression.

9.3 Results

9.3.1 Tree-ring formation

On the microphotographs, there are two growth zones visible after the cambial mark (Figure 9.5). These growth zones provide evidence for the formation of annual growth rings because they match with two rainfall peaks between marking and sampling of the trees. The first ring corresponds with the kiremt rain season in 2012 and the second ring with part of the kiremt season in 2013. However, the growth zones appear disturbed in response to the cambial pinning. The tree ring of 2012 directly after the pinning is relatively small and vessel size and density are relatively limited after marking.

The annual *Erica arborea* tree rings are mainly marked by radially flattened fibers in the last layers of the latewood and by changes in vessel density. The vessel density is especially higher in the earlywood and decreases towards the latewood (Figure 9.6). If a layer of flattened fibers is unclear or missing between two rings, this corresponds with an intra-annual density fluctuation (IADF) (Figure 9.6).

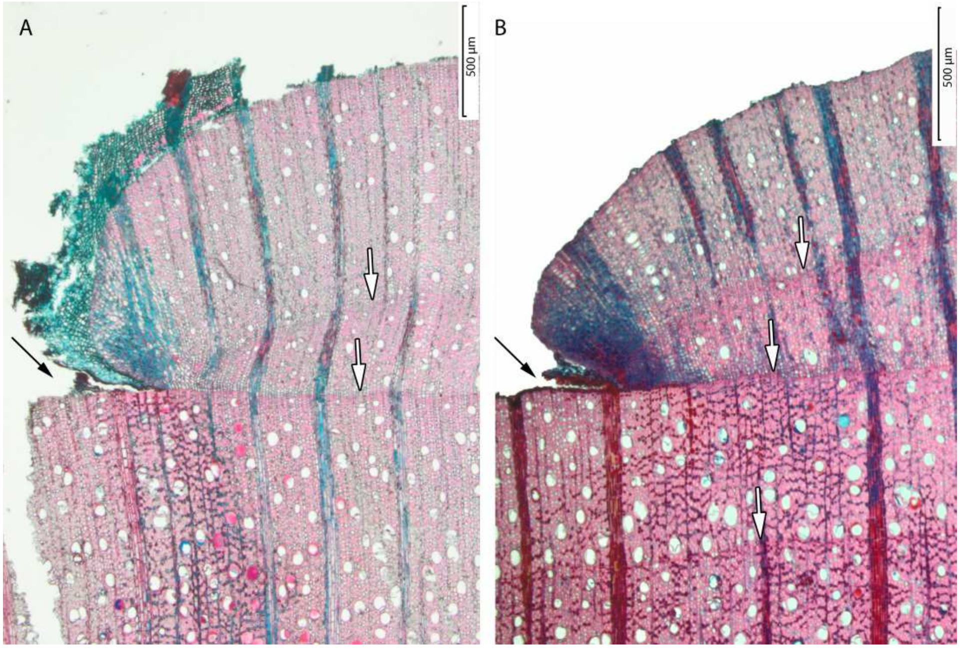

Figure 9.5 Microphotograph of the wound tissue formed in response to the cambial pinning. The cambial mark is indicated with black arrows in (A) sample Tw64884 and (B) sample Tw64881. The trees were marked on March 15 2012 and sampled after 498 days on July 25 2013. The tree-ring boundaries are indicated with white arrows.

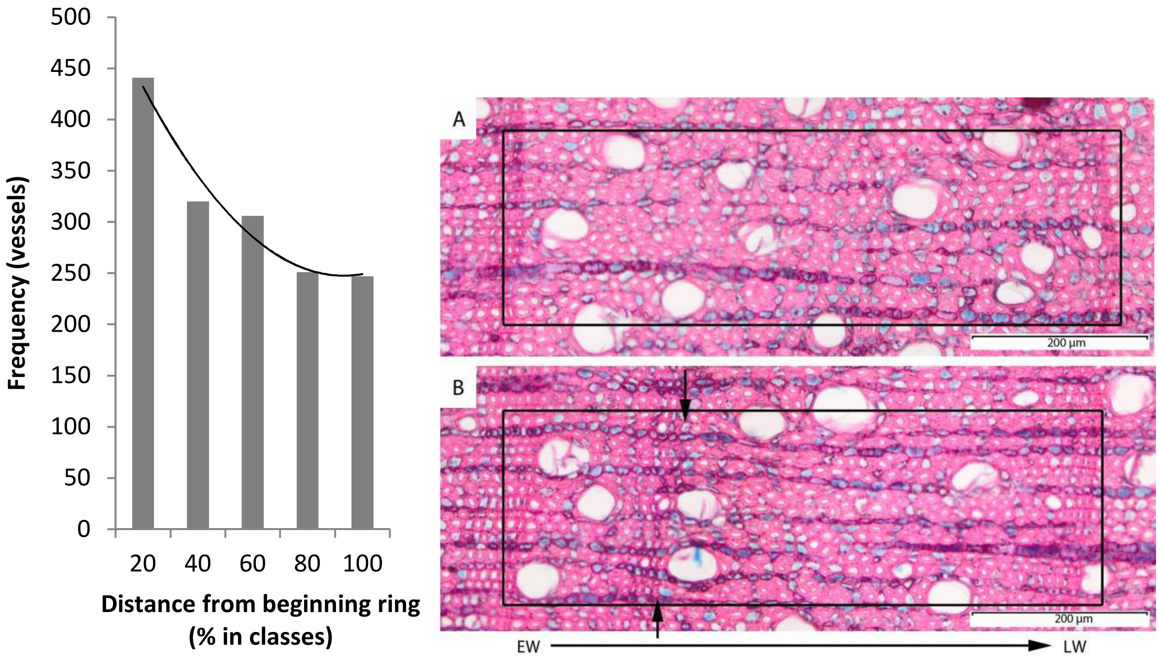

Figure 9.6 (left) Variability of the vessel density within a tree ring from the start (0%) to the end of a growth ring (100%) as derived from measurements of 50 tree rings;(right) Microphotographs from sample TW64881 showing a typical tree ring (A) without IADF in 2011 and (B) with IADF in 2009. Figure composition is based on De Micco et al. (2014). The location of the IADF in B is indicated with two arrows.

A dispersion graph is used to characterize vessel distribution in IADFs based on 50 tree rings of 3 samples (Figure 9.7). For this graph, IADFs with a clear growth interruption (24% of total tree rings) are combined for all measured years. Partial IADFs (40% of total tree rings) are excluded from the dispersion graph, but are very common and disturb the overall picture. On the dispersion graph the normal rings without IADFs (36% of total tree rings) are also plotted as a reference. From this graph, it becomes clear that IADFs typically occur at the beginning of the annual ring (early-IADFs). The graph also shows that vessel lumen area in normal tree rings decreases from earlywood to latewood.

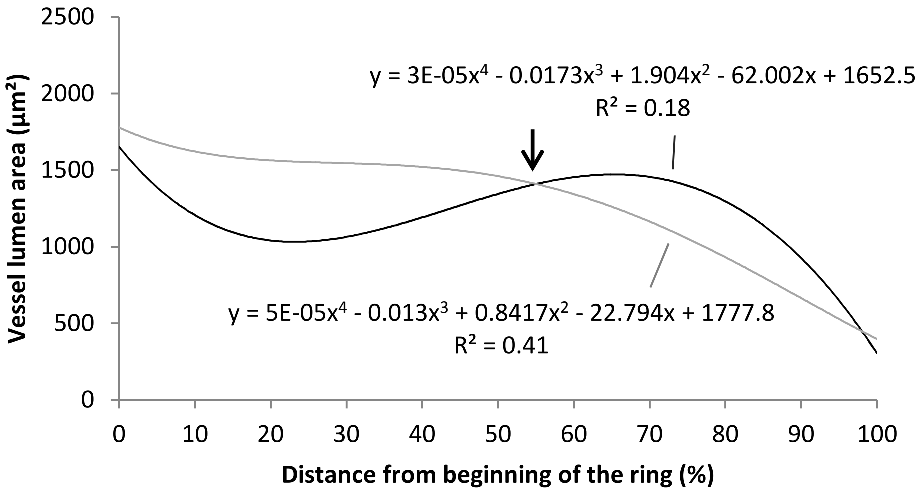

Figure 9.7 Dispersion graph of tree-ring formation in *Erica arborea* showing the vessel lumen area in relation to the distance from the beginning of the tree ring. The dispersion graph indicates in black the polynomial interpolation line for tree rings with IADFs and in grey the polynomial interpolation line for tree rings without IADFs. The arrow points to the end of the IADF.

9.3.2 IADFs and rainfall variability

IADFs form a major problem for dating tree rings since they are morphologically similar to latewood. In order to understand the formation of early-IADFs in the tree rings, the irregular first rain season (azmera) is evaluated as potential explaining factor. Rainfall patterns and rainfall-derived indices between 1997 and 2013 are presented in Table 9.2, together with tree-ring derived data. An 'N-1' chi-square test indicates that there is a significant relation between the occurrence of IADFs and dry spells (Chi^2=4.45, $p<0.05$). This relation is confirmed by the Phi coefficient, there is a significant weak positive association (ϕ: 0.55, $p<0.05$) between IADFs and dry spells. This means that the possibility of an IADF increases if there is a rainfall interruption of more than 20 days between the azmera and kiremt rainfall season. A binary logistic regression indicates that the combined effect of the amount of azmera rainfall, dry spell and rainfall dip is significant (Chi^2=9.99, $p<0.05$) and related with IADF formation (Nagelkerke R^2=0.65, classification accuracy 87.5%). Similar regressions indicate that there is no significant relation between IADF formation and respectively annual rainfall (R^2=0.01; $p>0.05$), kiremt rainfall (R^2=0.09; $p>0.05$) or azmera rainfall (R^2=0.02; $p>0.05$). IADF formation appears thus the result of the combined effect of azmera rainfall followed by a dry spell.

Table 9.2 Rainfall indices (from the Lalibela station) and IADF formation

	Total rainfall (mm)	Azmera rainfall* (mm)	Dry spell (<1mm) in days		Rainfall dip	Dry spell	IADF
			azmera	kiremt			
1997	1002.1	178.6	14	19	1	0	0
1998	789.8	81.4	17	23	0	1	1
1999	793.7	23	42	21	0	1	1
2000	693.9	60.6	28	9	0	0	0
2001	993.9	115.6	25	15	0	0	1
2002	722.1	87.1	29	14	0	0	0
2003	868.8	104.1	18	14	1	0	0
2004	567.3	35.3	38	15	0	0	0
2005	774.3	150.1	20	17	1	0	1
2006	851.3	97.2	17	13	0	0	0
2007	837.6	50.3	16	15	0	0	0
2008	704.4	79.8	38	14	0	0	0
2009	575.5	53.3	33	24	0	1	1
2010	771.7	78.9	17	15	0	0	0
2011	784.7	200.0	13	13	1	0	0
2013	1075.6	100.2	23	12	1	0	0

9.3.3 Dendrochronology

Despite the tropical environment and the limited success in previous studies, tree-ring series from stem disks and tree cores were successfully crossdated into a 48-year old tree-ring chronology (Table 9.3). From the 30 measured samples, 60% was included in the average combined tree-ring chronology (Figure 9.8). The tree-ring series of the excluded samples (40%) did not match the average tree-ring pattern (Glk>60, tBP<2). The combined chronology reveals no strong age trend (all AC values are below 0.5, Table 9.3) and the change in Mean Sensitivity (MS) before and after standardization is only 1%. The EPS of the crossdated trees is lower than the required threshold of 0.85. However, despite low cross dating values (low correlation values, no significant Pearson correlation), visual inspection (De Ridder et al., 2014) confirms correct crossdating between the trees.

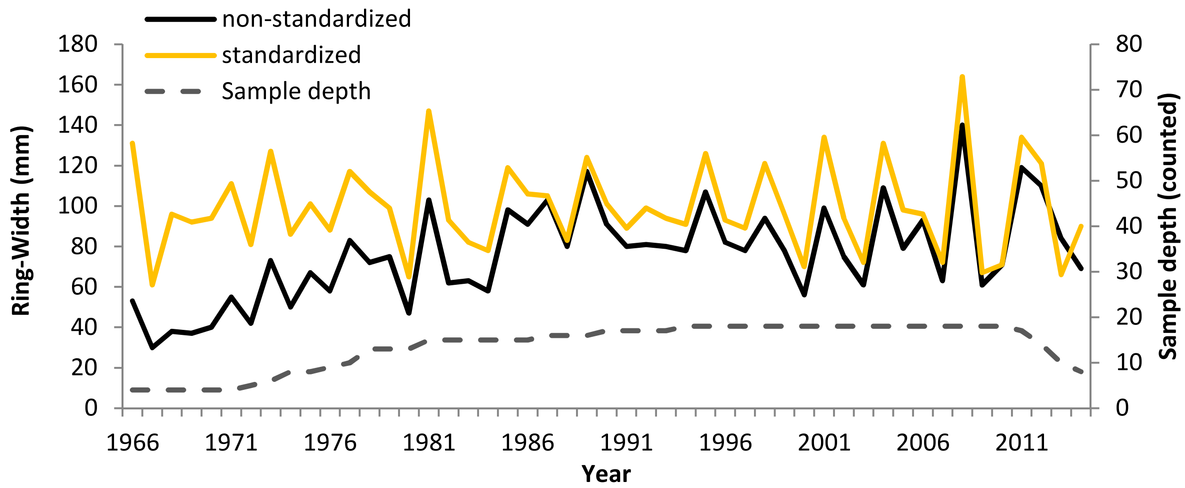

Figure 9.8 Tree-ring chronology of *Erica arborea* in the North Ethiopian highlands (1966-2014). On the graph, the non-standardized tree-ring chronology is given in black and the standardized chronology in orange. The sample depth is given with a dashed line, a minimum of 4 samples per year is used as threshold.

Table 9.3 Characteristics of the *Erica* chronologies for the stem disks, the tree cores and the combined chronology

	Stem disks	Cores	Combined
Total *n* tree samples	10	20	30
n samples in chrono	6 (60%)	12 (60%)	18 (60%)
Mean number of tree rings	46 ± 11	36 ± 9	39 ± 11
Time span chronology	1972 - 2012 (40 years)	1976 - 2014 (38 years)	1966 - 2014 (48 years)
Mean ring width chronology (mm)	0.48 ± 0.15	1.03 ± 0.26	0.76 ± 0.24
AC[1] before standardization	-0.01	-0.23	0.27
MS[2] after standardization	35	33	29
Pearson r[3]	0.20	0.07	0.08
EPS[4]	0.60	0.46	0.63

[1]Autocorrelation; [2]Mean Sensitivity; [3]Pearson correlation between trees; [4]EPS expressed population signal

9.3.4 Dendroclimatology

The NMA data of Maychew is used to derive the climate effect on tree growth, since Maychew has the longest climate record (1992-2013). Moreover, during the crossdating process tree growth is proven to be more sensitive to climate patterns under limited conditions higher up the mountain and more northerly in Ferrah Amba Mt., near to the Maychew station (higher Glk. and tBP values).

The tree-ring chronology is significantly ($p < 0.1$) correlated with minimum temperature in March and August (Figure 9.9). In March, during the azmera season, this correlation is negative and in August, in the kiremt season this correlation is positive. For the maximum temperature and for rainfall there are no significant correlations with tree growth. There are also no significant correlations ($p > 0.1$) between tree growth and the Martonne Aridity Index. A multiple linear regression with minimum temperature in March and August is significant and is able to explain 24% of the variation in tree growth (R^2: 0.24; $p<0.05$).

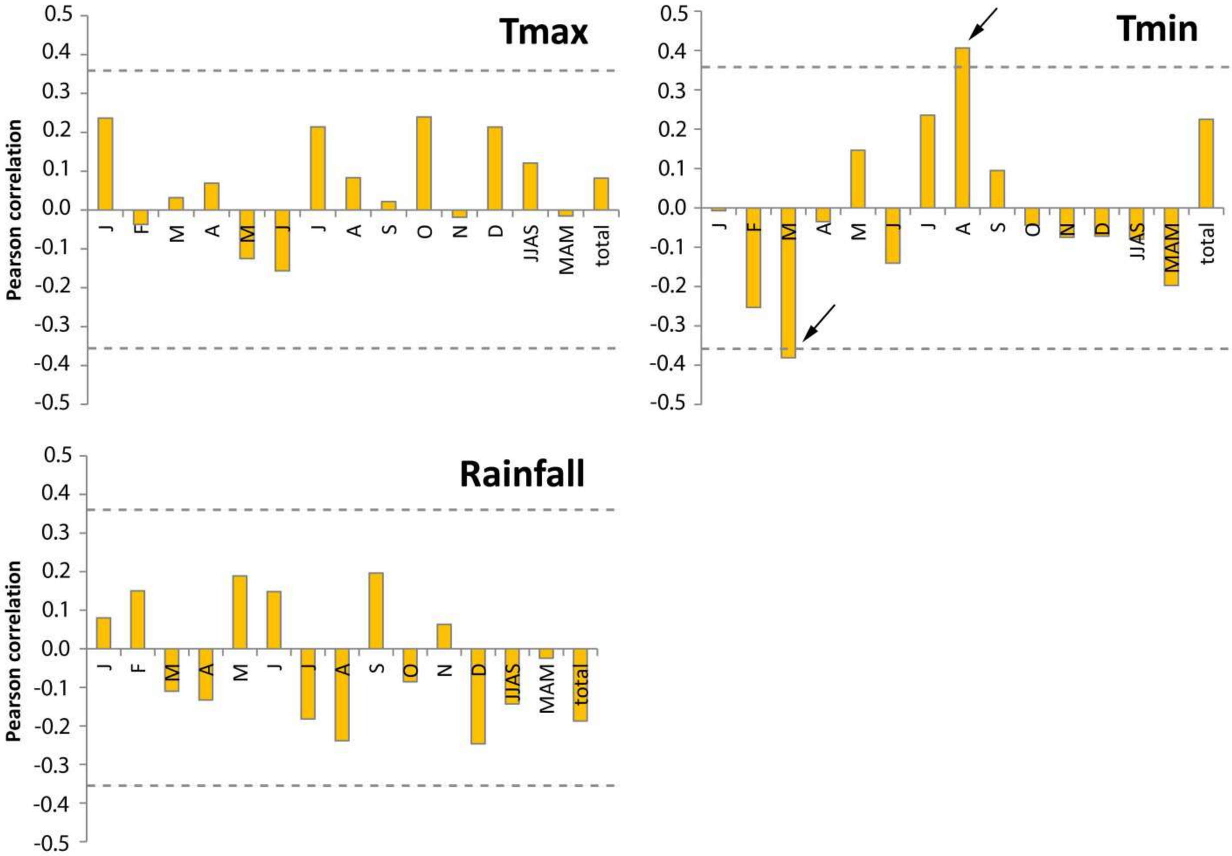

Figure 9.9 Correlation coefficients (n = 22) between monthly and seasonal climate variability and tree-ring width of *Erica arborea* (1992-2013). (A) Maximum temperature; (B) Minimum temperature; (C) Rainfall. The dotted line represents the $p<0.1$ level. Significant correlations are indicated with a black arrow.

9.3.5 Tree growth gradient

Tree height decreases with increasing elevation by approximately one meter along a vertical gradient of 100 m (Figure 9.10). But, the observed relation between tree height and elevation is not strong (R^2= 0.30, p<0.05). The height-age curve shows no significant correlation between tree heigth and tree age for trees older than 20 years (Figure 9.10). Lower tree heights at higher elevations are thus not directly related wtih younger trees at the treeline.

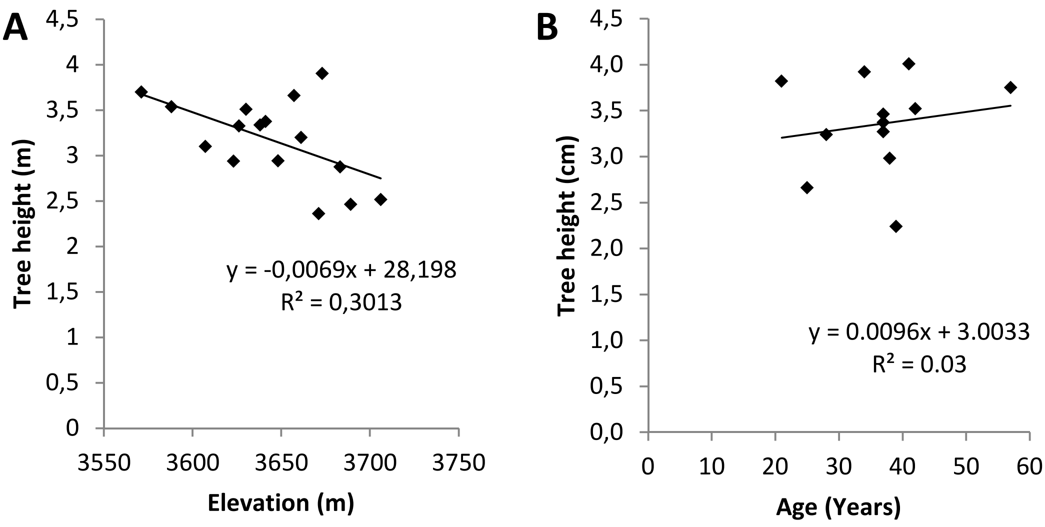

Figure 9.10 (A) Tree height versus elevation and (B) tree height versus age

9.4 Discussion

Radially flattened fibers in the last layers of the latewood mainly characterize the tree-ring boundaries of *Erica arborea* in the tropics. In the Mediterranean, *Erica* tree rings are typically formed by a transition of vessel density and size from earlywood to latewood; vessel density and size are higher in the earlywood and decrease towards the latewood (Battipaglia et al., 2014). A similar transition is observed for *Erica arborea* in the tropics, but less pronounced. The possibility for IADF formation in *Erica* in Ethiopia is higher when there is a dry spell between the azmera and kiremt season and especially when this is combined with high rainfall amounts during the azmera season. Similarly, the formation of IADFs in the Mediterranean is also related to drought stress (Battipaglia et al., 2014). IADFs in the Mediterranean form as the combined result of high temperature in the summer, rainfall and soil water variability. The formation of IADFs is much higher (with more than 70% of the total rings) in the Mediterranean region (Battipaglia et al., 2014) in comparison to IADF formation in the tropics (24%).

The tree-ring chronology presented here is not the first for *Erica arborea* in the tropics. Kaeppeli (1998) made a chronology of *Erica arborea* in 1998 spanning a period of 20 years (1976-1996) at Nebir Mekemecha (3800 m a.s.l.) in the Simen Mts. This tree-ring chronology of Kaeppeli (1998) was used to compare with the overlapping chronology established in this study; however the correlation is very weak (Pearson r = 0.04). This can be addressed to the variable climatological conditions in the Simen Mountains (Chapter 8). Kaeppeli (1998) did not consider dendroclimatology with *Erica arborea* due to wedging rings, human impact and the occurrence of IADFs. Whereas, this study indicates that *Erica arborea* could potentially be used for dendroclimatology. The relation between tree growth and minimum temperature is only significant on the $p<0.1$ significance level. This limited significance is mainly due to the restricted available climate data of only 22 years (1992-2013), while the chronology spans a period of 48 years (1966-2014). The low EPS might also explain the low correlation with climate because the sample size is small and possibly not representative for the whole population of *Erica arborea*. Nevertheless, at the $p<0.1$ significance level there are two significant relations between tree growth and minimum temperature. There is a positive correlation between tree growth and minimum temperature in the growing season (August). A similar positive relation between temperature and *Cedrela montana* tree growth in the growing season is observed in the humid mountain rainforests of southern Ecuador by Bräuning et al. (2009). This indicates that the minimum temperature in the growing season controls tree growth and that warmer temperatures can enhance growth. In March, there is a negative relation between minimum temperature and tree growth. This is potentially related with the formation of IADFs. However, more research is required to verify this relation.

The environmental lapse rate of temperature is -0.72°C per 100 m for the study area, whereas for rainfall there is no significant trend with elevation (Chapter 8). The rainfall patterns in Maychew are therefore not suitable to understand the relation with tree growth at the afro-alpine forest. Rainfall data from near to the forest is needed to understand the impact of rainfall patterns on tree growth. The effect of rainfall on tree growth is indicated to be positive in subtropical treelines in Northwestern Argentina (Morales et al., 2004), but negative in the humid mountain rainforest in southern Ecuador (Bräuning et al., 2009). The difference between these studies is caused by different rainfall conditions. In Northwestern Argentina rainfall strongly decreases with elevation up to <200 mm above 4000 m, whereas in southern Ecuador average annual rainfall exceeds 2000 mm (Morales et al., 2004; Bräuning et al., 2009). Rainfall thus impedes tree growth under wet conditions and enhances tree growth under dry conditions. This trend is also visible in the correlation between tree growth and rainfall variability (Figure 9.9). In the azmera and kiremt rain season tree growth is negatively correlated with rainfall (however this relation is not significant). This indicates the need for detailed climate data at higher elevations. The strength of the correlation would potentially rise if more climate data would be available at high elevations and if more samples were included. An improved correlation between tree growth and climate could potentially allow climate reconstructions as given by Schöngart et al. (2006) for West Africa.

The size of the trees decreases with one meter over 100 vertical meter towards the treeline, this is in line with treeline studies in the European alps (Paulsen and Körner, 2014). The height of the tree is not significantly related with the age of the tree for trees older than 20 years. Smaller trees at the treeline are thus not necessarily younger. There is thus no evidence for an upwards shift of the treeline based on the sampled trees. This might be because there were only three trees younger than 32 years sampled and the expansion of the forest and upwards movement of the treeline mainly occurred between 1982 and 2014 (Chapter 11).

9.5 Conclusion and outlook

The presented 48 years tree-ring chronology of *Erica arborea* (1966-2014) proves the potential of tropical *Erica* trees for dendrochronology. Stem disks and increment cores were collected in the tropical highlands of North Ethiopia in Lib Amba and Ferrah Amba Mountain. The formation of annual growth rings is proven by microphotographs of cambial marked stem disks. *Erica arborea* tree rings are characterized by radially flattened fibers in the last layers of the latewood and by decreasing vessel density and size from earlywood to latewood. IADFs are observed in relation with early rainfall followed by a dry spell. Tree growth is significantly and positively related with minimum temperature in the growing season, but negatively with tree growth in the azmera season (potentially explaining higher risks for IADF formation). Rainfall had a negative impact during the rain season, but more research is needed to understand the rainfall effect. The *Erica arborea* chronology presented in this study provides a successful example for further dendrochronological studies. IADF formation shows the best opportunities for climate reconstructions. Wood density measurements and repeated cambial pinning on more trees combined with site specific climate monitoring are suggested to further disentangle the link between climate and tree growth.

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Chapter 10 Land use and cover dynamics since 1964 in the afro-alpine vegetation belt of North Ethiopia

This chapter is based on:

Jacob, M., Romeyns, L., Frankl, A., Asfaha, T., Beeckman, H., Nyssen J. (2015). Land use and cover dynamics since 1964 in the afro-alpine vegetation belt: Lib Amba mountain North Ethiopia. Land Degradation and Development, accepted.

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* 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.

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

10.1 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 and Hedlund, 2000; Zeleke and 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 and 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 and 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., 2013b, 2011). 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 and 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 and 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 and Liberman, 2006). By storing rainfall, highland forests reduce soil erosion and form a buffer against flooding in lower areas (Aerts et al., 2002; Miehe and 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.

10.2 Materials and Methods

10.2.1 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 (Figure 10.1). 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 and 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 and 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., 2005, 2004).

Small scale agriculture dominates in the valleys up to 3500 m, which is the altitudinal limit of barley (Hurni and 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 and CIAT, 2005).

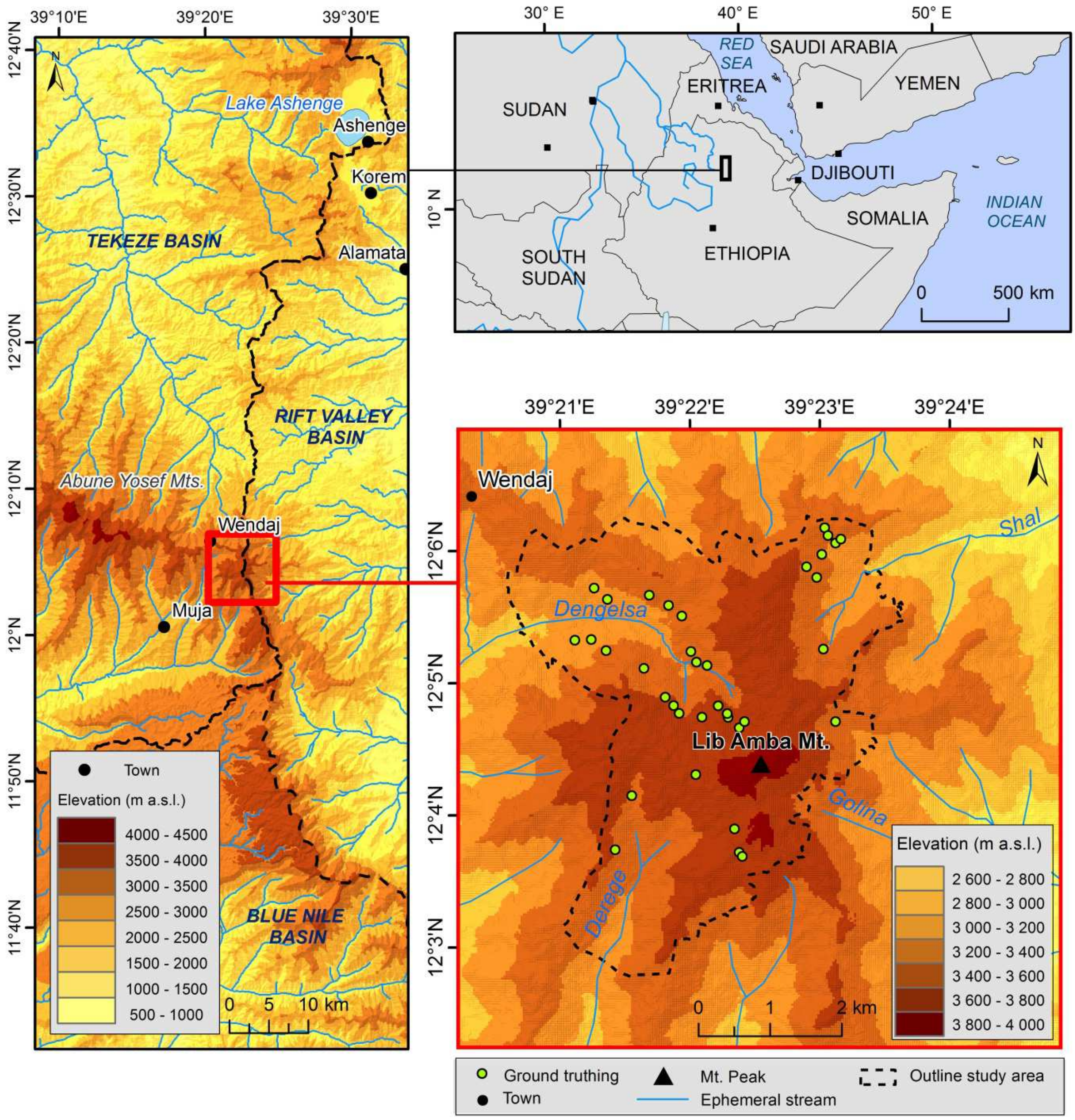

Figure 10.1 Location of the study area

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 (Chapter 5). 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 (Figure 10.2A). 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) (Figure 10.2B). A unique specie in the afro-alpine zone is giant lobelia (*Lobelia rhynchopetalum Hemsl.*), which can mostly be found at wetter depressions

(Figure 10.2C). At high altitudes the vegetation dominated by afro-alpine tussock grasses that are well adapted to the cold mountain environment (Friis et al., 2010) (Figure 10.2D).

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 and Sillero-Zubiri, 2014), other well-known endemic species encountered in the study area are the Gelada baboon (*Theropithecus gelada*) and the Abysinian owl (*Asio abyssinicus*).

Figure 10.2 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*).

10.2.2 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 10.1). 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 10.1).

Table 10.1 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

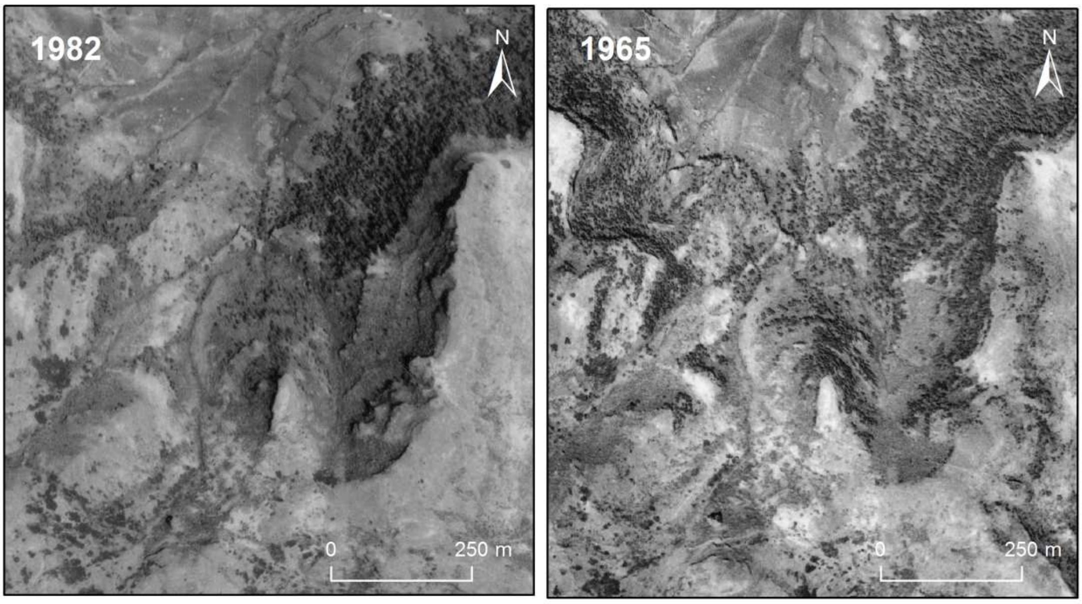

Figure 10.3 Illustration of two overlapping aerial photographs for a subset area northeast of Lib Amba Mountain (left) Image from 25 January 1982 (ET2-S12-30-0435, NMA) and (right) Image from 20 February 1965 (R-153-14479, NMA).

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).

10.2.3 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.

10.2.4 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 and 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.

10.2.5 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 (Figure 5.3).

10.3 Results

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

The LUC of Lib Amba Mt. was mapped for the three successive periods (Figure 10.4). 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.

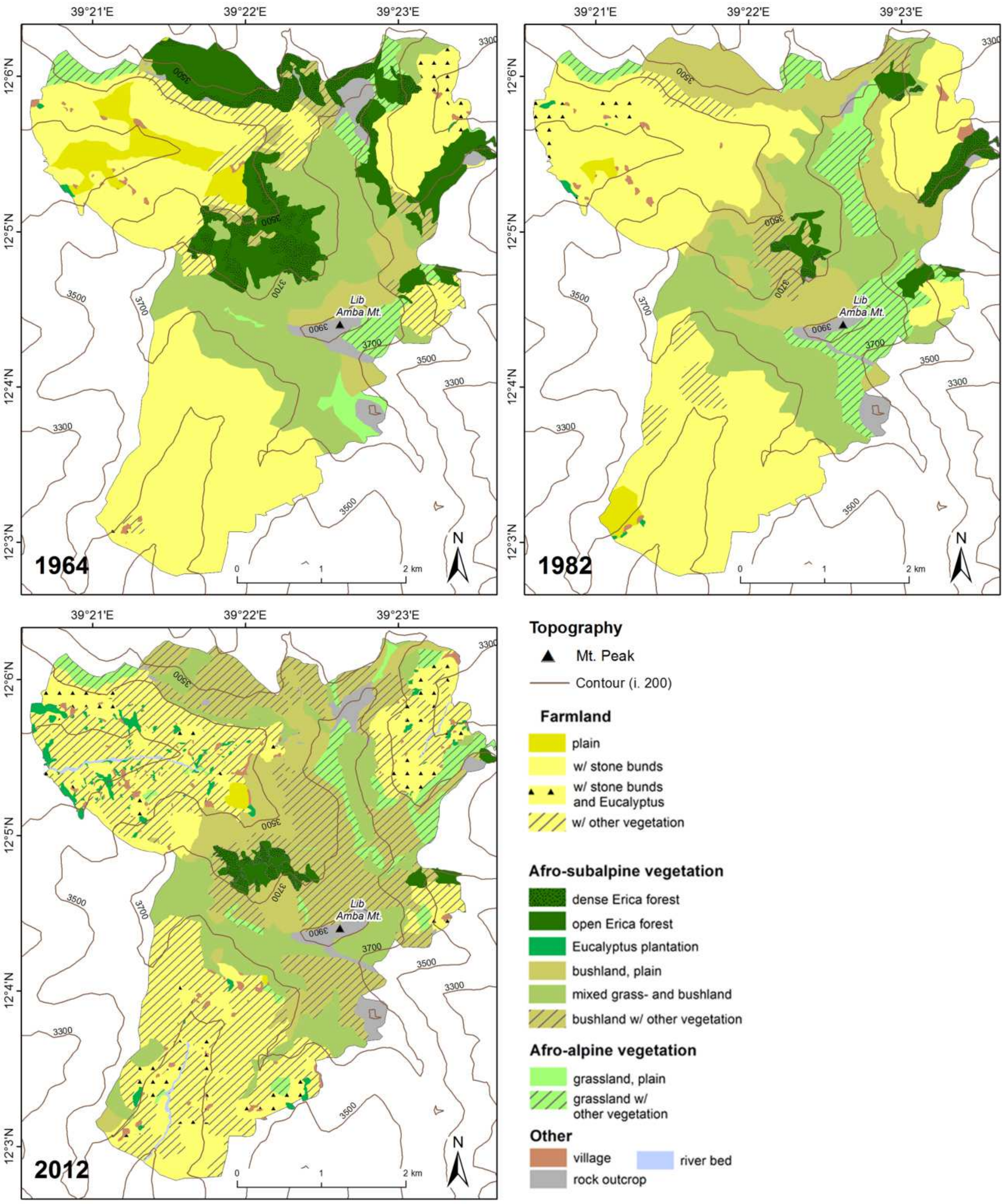

Figure 10.4 LUC maps for the three successive time steps (1964, 1982 and 2012)

10.3.2 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 (Figure 10.5). 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.

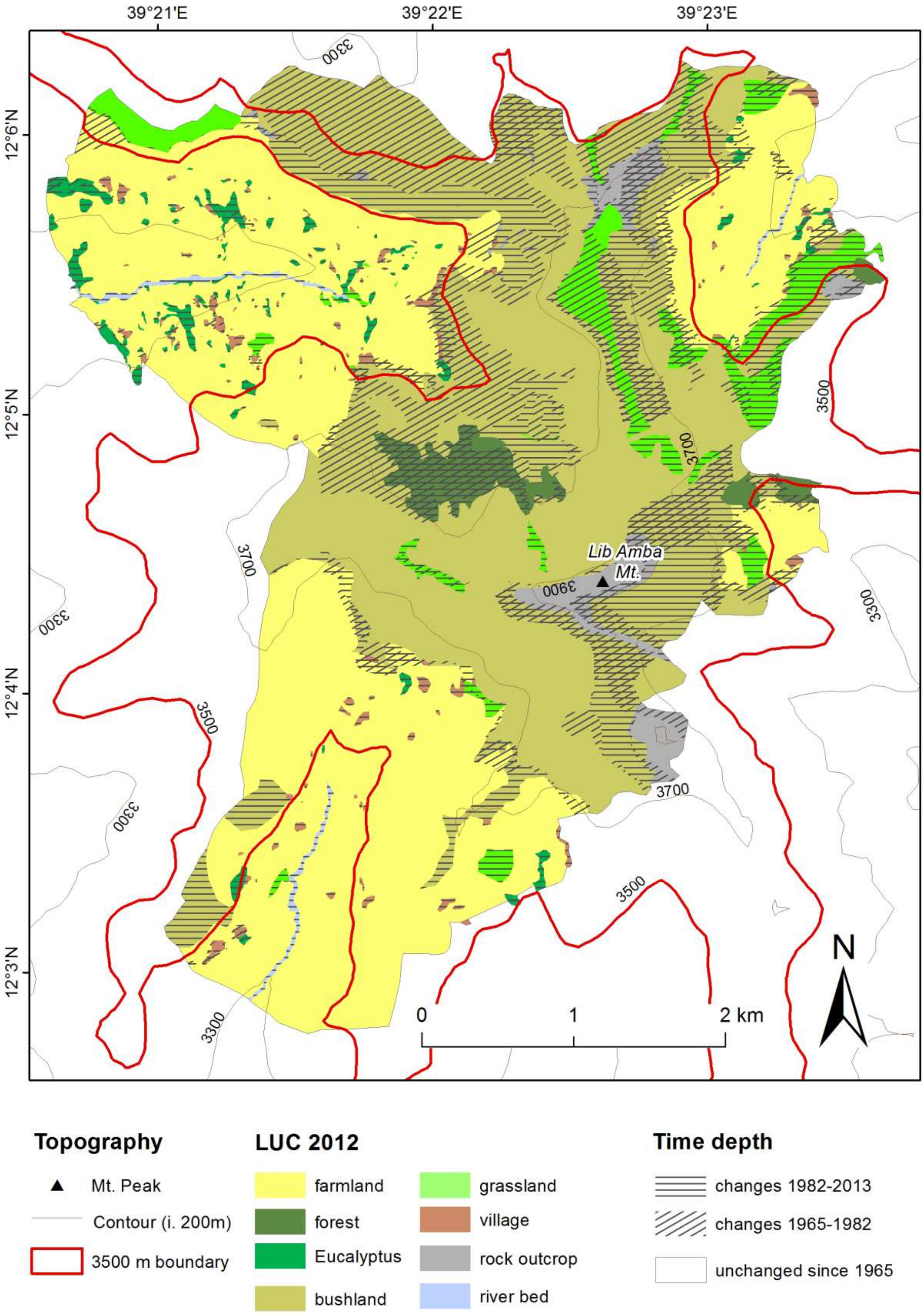

Figure 10.5 Time depth map of the LUC between 1964 and 2012

The proportions of every LUC class of 1964, 1982 and 2012 reveals the major trends in the study area (Figure 10.6). 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.

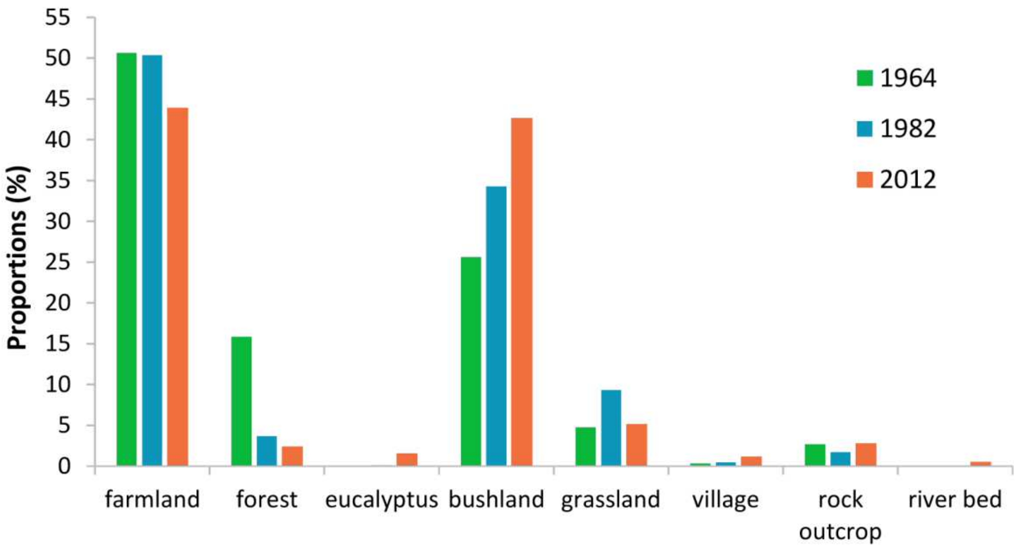

Figure 10.6 LUC class proportions for 1964, 1982 and 2012

LUC transition matrices and change maps reveal the nature of the long-term changes between 1964 and 2012 (Table 10.2). 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 (Table 10.3). 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 approx. 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 %).

Table 10.2 Land use and cover transition matrix of the entire study area 1964-2012 (surface area in percent). 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 10.3 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.

	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

Eight LUC-trajectories explain 98.2 percent of the LUC changes (Table 10.4). 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 10.4).

Table 10.4 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* 1964		1982		2012	*Percentage of study area (%)*
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

10.3.3 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 (1991), 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.

10.4 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 10.7 summarizes the main trends by plotting the LUC proportions in time for the two elevation zones separately.

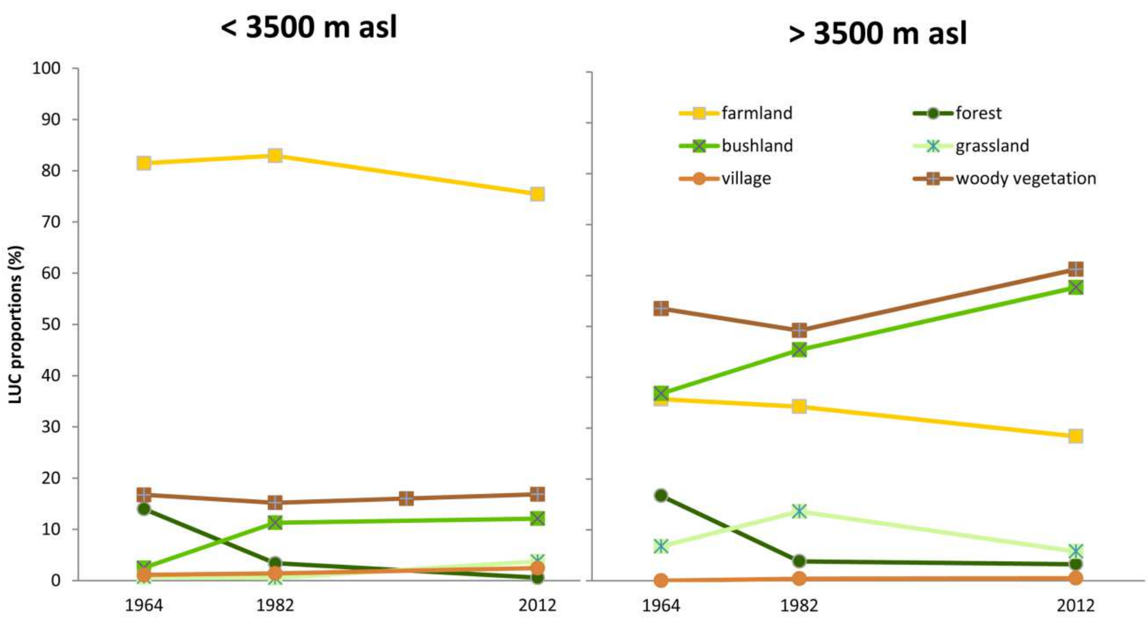

Figure 10.7 Overview of the most important LUC changes between 1964,1982 and 2012. Woody vegetation is the sum of the proportions of forest, bushland and Eucalyptus plantation.

10.4.1 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 and 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 mainly by the abandonment of degraded lands with a low yield on steep slopes. The growing population also causes a conversion of farmland into settlements, but this fraction is very small (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 (Boserup, 1965), 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).

10.4.2 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 (Figure 10.8). 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).

Figure 10.8 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.

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 and 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.

10.5 Conclusion

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* 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 indicates the 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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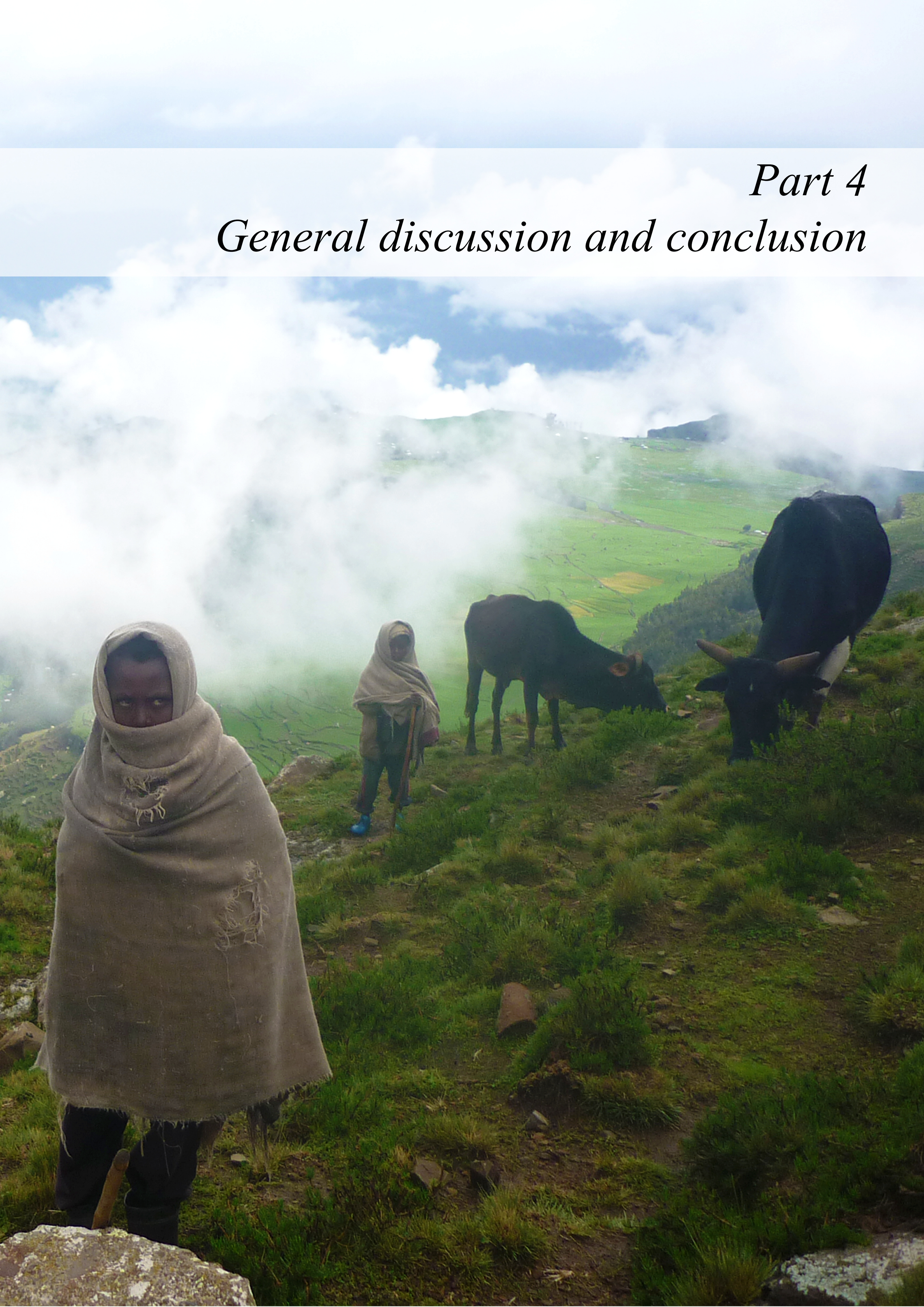
Part 4
General discussion and conclusion



The photograph on the back of this page is taken at the slopes of Ferrah Amba Mt. looking to the south at an elevation of 3750 m a.s.l. (12°51’39”N, 39°29’06”E), on the 4th of August 2013. The cattle on the photograph illustrate the home-range herding movement of the people in the surrounding villages to the afro-alpine grassland at the top of the mountain.

Chapter 11 General discussion and conclusion

11.1 General summary

The state of the art about treeline dynamics and the environmental setting of the study area are presented in the first part. In general, on the scale of tropical Africa, the treeline is not rising to higher altitudes, despite recent climate warming. On the contrary, high human pressure has caused stabilization and even recession of the treelines below their natural climatic limit, particularly through livestock herding (Chapter 2). In addition, on the scale of the study area in the North Ethiopian highlands, the geomorphological setting and the forest physiognomy were mapped in detail (Chapter 3 and 4). It is in this broad setting that the dynamics and drivers of high altitude forest cover change and treeline shifts since 1964 are reconstructed. The afro-alpine forest declined between 1964 and 1982 and extended afterwards between 1982 and 2015, while the opposite trajectory was observed in the lower afromontane forest belt (Chapter 5, 6 and 10). The treeline is indicated to have shifted upwards up to 4000 m a.s.l. locally in the Simen Mts. (Chapter 6), but in general, the treeline is located 400 m below its potential climatic position (Chapter 8). The potential climatic limit is a temperature limit, since temperature during the growing season is indicated to limit tree growth, as observed from dendrochronology analysis (Chapter 9). A 48 years tree-ring chronology of *Erica arborea* (1966-2014) was established and annual growth ring formation is proven by microphotographs of cambial marked stem disks. However, IADFs are observed in relation with early rainfall followed by a dry spell, which can disturb ring formation. Tree growth is significantly and positively related with minimum temperature in the growing season, but negatively with tree growth in the azmera season (potentially explaining higher risks for IADF formation) (Chapter 9). Based on the environmental lapse rate of air temperature, 0.72°C per 100 m, was the potential climatic limit of the treeline reconstructed at 4100 m a.s.l. This means that the current treeline elevation is depressed by 400 m below its potential climatic limit (Chapter 8). To study the effect of rainfall on tree growth at the treeline, calibrated satellite-derived RFE were evaluated. However, because they underestimate rainfall in mountainous areas the calibrated RFE are not used for the study area (Chapter 7). Instead, meteorological station rainfall data was collected. But, rainfall data did not significantly relate with elevation (Chapter 8). The currently depressed treeline elevation can be attributed to the effect of changing population dynamics (Chapter 10).

11.2 Conceptual model of mountain forest dynamics

The main results are combined in a comprehensive conceptual model (Figure 1). This model presents the altitudinal limitations and changes in the upper mountain forest belts of North Ethiopia for three time steps and provides scenarios of future changes under different management strategies. The mountain forest belt limitations in 1964 are used as hypothetical reference situation in the first time step (I). In the following two time steps, the changes in mountain forests and treelines are presented for respectively 1964-1982 (II) and 1982-2015 (III). A projection of future mountain forest belt dynamics is given for three scenarios. In scenario (A), the protected area is extended including the lower afromontane *Juniperus* forest belt. In scenario (B), the protected area is limited to the afro-alpine *Erica* forest which corresponds with a continuation of the current management strategy, while in scenario (C) protection of the mountain forests is completely abandoned.

For the Simen Mountains, Hurni and Stähli (1982) characterized the altitudinal limits and belts for the Late Würm and for the 1982 situation; this method was adapted here. In the model, two hypothetical mountains are presented with different elevations. The smaller mountain represents mountains peaking at approx. 4000 m a.s.l., as observed in Lib Amba (Chapter 5 and 10), while the larger mountain peaks at approx. 4500 m a.s.l. and represents protected mountain ranges as observed in the Simen Mountains (Chapter 6). Arrows are used to indicate changes of the mountain forest: lateral arrows represent expansion or contraction of the forest and vertical arrows represent upwards shift or depression of the (upper and lower) altitudinal forest limit. The arrows are colored in red and green to emphasize, respectively, 'positive' and 'negative' effects.

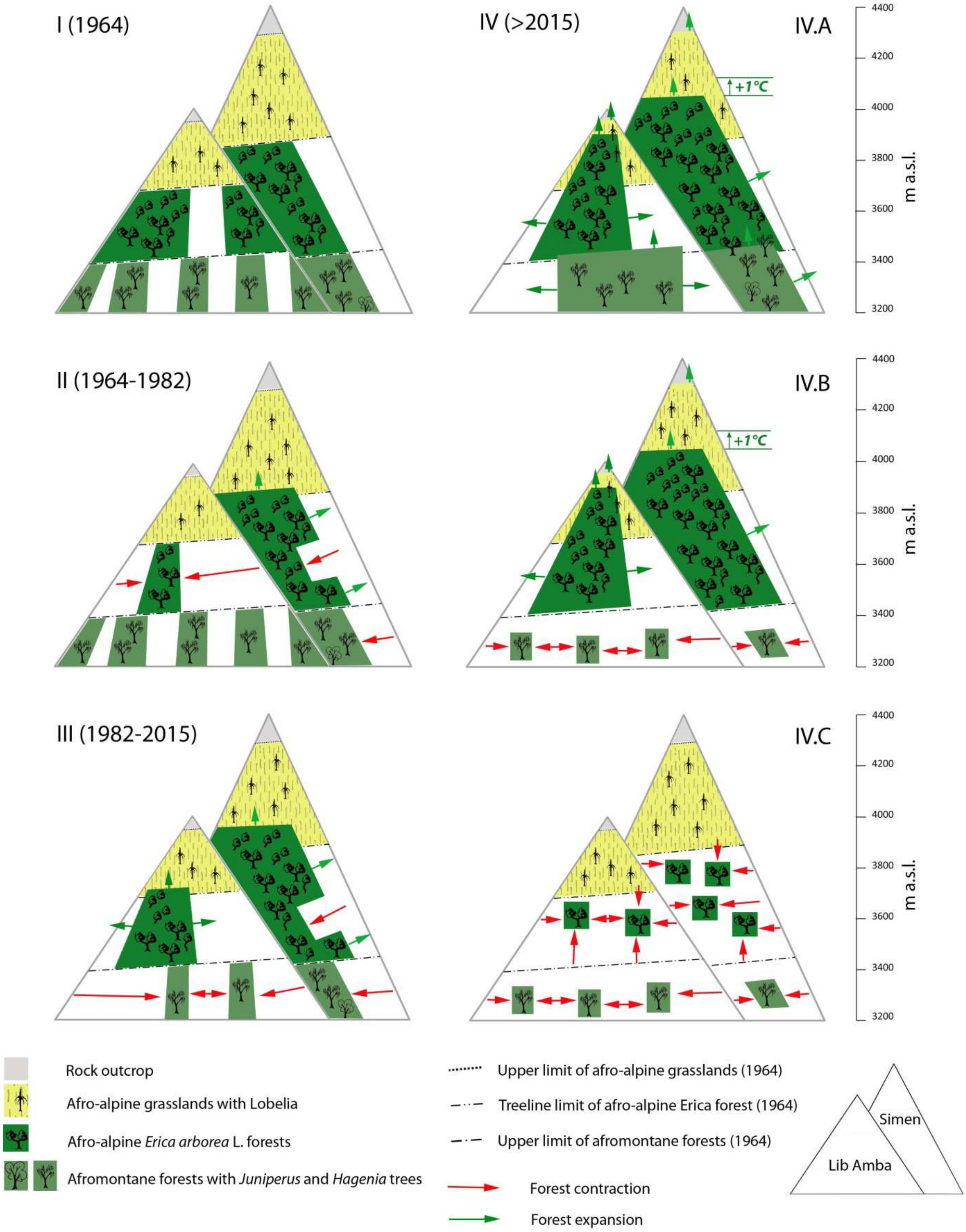


Figure 11.1 Conceptual model of mountain vegetation dynamics in the North Ethiopian highlands

Below, the different time steps are explained in detail.

Time step I (1964)

Data on mountain forest dynamics from before 1964 are scarce for the study area. A historical terrestrial photograph of 1917 looking towards Aboy Gerey Mt. (3565 m a.s.l.) gives indications for a late human colonization of the upper mountain area (Chapter 5, Figure 5.2). The altitudinal vegetation belts for this first time step are based on data from Chapter 5 and 6. These vegetation belts form the reference situation of the model. The altitudinal limit is different for the two mountains because the spatial extension of the *Erica* forest is smaller for Lib Amba in 1964.

Time step II (1964-1982)

In this period the afro-alpine *Erica* forest strongly declined (from 16% to 4%) on unprotected slopes (Chapter 10). The main driver responsible for this deforestation trend is a population shift upward the mountain due to increasing scarcity of land and resources in the lower areas. These observations can be explained in a political ecological framework (Lanckriet et al., 2014) and correspond with the first phase of the neo-Boserupian perspective (Chapter 10). The political power in this period switches from the late feudal regime (until 1974) to the early Derg regime (1974-1991). In the feudal period land inequity, lack of centralized conservation policies and sharecropping systems hindered long-term conservation investments and caused land degradation (Lanckriet et al., 2014). Subsequently, during the civil war under the Derg regime, inherited exhausted lands and economic stagnation further aggravated land degradation (Lanckriet et al., 2014). The upwards movement of farmers is caused by unequal land rights, pushing the poor farmers to steep slopes and marginal terrains in the feudal period (Lanckriet et al., 2014). Following neo-Boserupian theory, extensive land clearing (deforestation and degradation) prevails during human colonization under relatively low population densities; while necessity under increased population pressure, drives farmers to invest in better land management and agricultural intensification. During the period 1964-1982, under extensive population pressure (first phase of the neo-Boserupian perspective) and lack of centralized conservation (political ecological model), the afro-alpine forests strongly degraded.

Under protected conditions in the Simen Mountains, the afro-alpine *Erica* forest expands in this period. However, locally continued anthropo-zoogenic pressure causes a decrease of the woody vegetation. In this period, the upper treeline increased (more than 1 m year^{-1}) in local areas isolated from anthropo-zoogenic pressure (Chapter 6). The unprotected afromontane forest beneath the protected afro-alpine forest slightly decreased (Chapter 6).

Time step III (1982-2015)

Although population pressure in the highlands continued to increase (Chapter 5, Figure 5.8), woody vegetation cover increased in the afro-alpine belt (with almost 13%) in this period (Chapter 10). The remaining afro-alpine *Erica* forests are protected, which resulted in forest regeneration and a small increase (up to 0.5 m year^{-1} since 1982) of the physiognomic treeline elevation (Chapter 5). This is in line with the second phase of the neo-Boserupian perspective (Chapter 10) and fits in the political-ecological model. Political power changed in 1991, in the post-war period the political-ecological system was re-organized with a new land reform and large scale investments in soil and water conservation (Lanckriet et al., 2014). However, due to complete closure of the upper forest, pressure increases at the unprotected afromontane Juniperus forests in the vicinity (forest cover decreased with 63%) (Chapter 5). Such a secondary effect must be taken into account for a sustainable management of these environments (Chapter 10).

In the protected environment of the Simen Mountains there is a continuation of the observed trends. The elevation of the *Erica* treeline even rises up to almost 4000 m a.s.l. The anthropo-zoogenic pressure continues in the afromontane forests and at local places in the afro-alpine forest, but outside of these areas the afro-alpine forest extends further (Chapter 6 and 7).

Time step IV (2015-future)

The observed forest dynamics between 1964 and 2015 were used to project the future forest cover under three different management scenarios. Associated with this projection, the potential environmental impact of the expected forest cover change on the mountain ecosystem is briefly addressed for each scenario.

Scenario A: extended protection with inclusion of the afromontane Juniperus forests

Quick recovery of the afro-alpine *Erica* forest in Lib Amba after protection (Chapter 10) gives evidence for an expansion of the forest under protected conditions, given the vicinity of remaining forest patches (Chapter 5). Similarly, the afromontane *Juniperus* forest is expected to recover and expand after protection. This would allow fragmented patches of forest to reconnect, which in turn would benefit wildlife populations in the highlands (Yihune et al., 2009). Extension of the mountain forest would also deliver benefits for the ecosystem services they provide (Chapter 1). The protection of forest on steep slopes is most important, because regeneration of forests on steep slopes helps to reduce run off (Chapter 4). This is even the case if soil depth is small, since *Erica* grows well on shallow soils (Chapter 4). An uplift of the treeline up to 4250 m a.s.l. is expected, taking into account an increase of the air temperature with 1°C since 2015 (Chapter 6 and 8).

Scenario B: unchanged protection with only the afro-alpine *Erica* forests protected

In this scenario, the afro-alpine *Erica* forests are protected and are able to expand. The treeline would rise, similarly as in scenario A up to 4250 m a.s.l. (taking into account a 1°C temperature warming). While, continued pressure on the lower afromontane forests would strongly reduce their spatial extent. This is more or less similar to the observations during the third time step (1982-2015). This land management scenario would limit the sustainability of the mountain landscape (e.g., Figure 11.2) and its ecosystem services on the long term.

Figure 11.2 Gullies are observed beneath deforested slopes, Ferrah Amba Mt. (February 26 2012).

Scenario C: non-protection

The third scenario, that involves a discontinuation of the protection of the mountain forests, would have devastating effects on the environment as well as for surrounding communities. This would cause aggravated habitat loss and critically endanger wildlife species such as the Walia ibex (*Capra walie*) and cause an overall decrease of biodiversity (Gebremedhin et al., 2010). The ecosystem would move out of balance, which could potentially trigger increased soil erosion, floods and a decrease of spring water affecting the vulnerable communities on the lower slopes.

11.3 Conceptual model validation

Italian aerial photographs from the 1930s are increasingly available thanks to a Memorandum of Understanding between the Ethiopian Mapping Agency, Ghent University and Mekelle University. In 2015, a unique 1938 aerial photograph of Mount Guna (11°42'N, 38°14'E, 4231 m a.s.l.) was retrieved from this collection, too late to include Mount Guna in the ongoing study. The aerial photograph was hence only used to validate the conceptual model. The local history of the treeline elevation that could be observed on the photograph was derived from aerial photographs of 1957 and 1980 and a recent Google Earth image (2014) (Figure 11.3). The forest history of Mount Guna is in line with the conceptual model (11.1). The treeline rose in the early feudal period between 1938 and 1957, which corresponds with a period of low anthropo-zoogenic pressure due to late colonization of the upper mountain areas. The forest also densified in this period, from an open grazed *Erica* forest to a closed forest. This is potentially related with protective measures at this period. In the late Feudal and early Derg regime, between 1957 and 1980, the density of the forest and the treeline strongly decreased. This is in agreement with the second time step; the population shifted upwards the mountain and severely impact the forests in the afro-alpine belt. Local informants claim that the forest nearly disappeared by the end of the 1980s. At present, in the post-war period, the forest densified and the treeline has risen to its highest elevation, above 3800 m a.s.l. (in 2014). This is in line with the third time step; forest protection and regeneration under increased population pressure.

The treeline in Mount Guna shifted up with approx. 80 m over a period of almost 80 years (1938-2014). The biggest advance of the treeline occurred between 1938 and 1957, in a period of limited anthropo-zoogenic pressure. Similar rates of treeline shifts (1 m year^{-1}) are observed in the Simen Mts (Chapter 6).

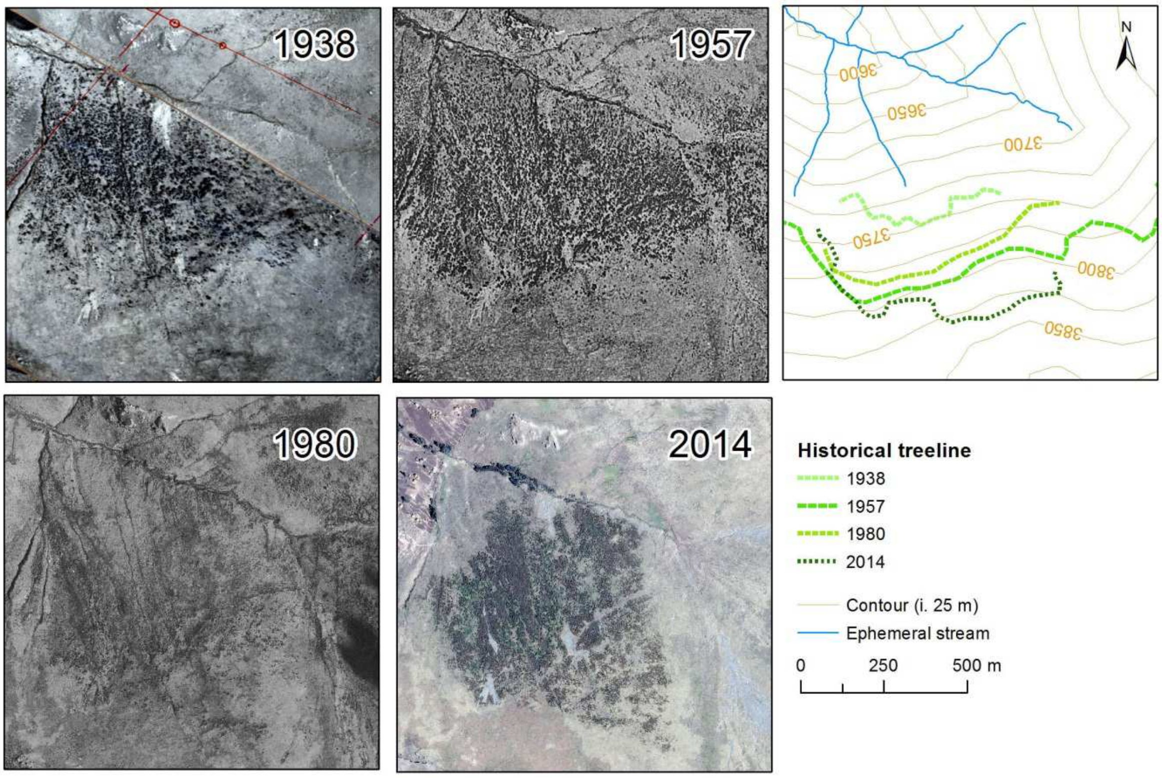


Figure 11.3 Treeline shift in Mount Guna as derived from co-registered historical aerial photographs. The 1938 aerial photograph was made by the Italian Military, the 1957 and 1980 aerial photographs are from the Ethiopian Mapping Agency (EMA) and the 2014 satellite image is from Google Earth.

11.4 Limitations to model application

The time steps presented in the model are based on data availability and therefore not necessarily converge with historical transition dates. Data with a higher temporal resolution is required to delimit the temporal scale of the transitions more precisely.

Another limitation is that the model focuses on different levels of protection, whereas also other factors can cause a forest transition. For example, economic development with land abandonment and migration to urban areas is what caused reforestation in the European and North American mountains (Mather, 2001). A similar forest transition is currently ongoing in many parts of Asia (Mather, 2001). However, to date Ethiopia remains largely under-urbanized, even according to African standards. This lack of urbanization can be partly attributed to the self-efficiency of agriculture and the 1975 land reform program, which provides incentives and opportunities for peasants in rural areas (Golini et al. 2001). It is estimated that the rural population in 2030 (83 millions) could still be almost the double of the urban population (45 millions) in Ethiopia (Golini et al.

2001). Subsequently, land abandonment and migration will probably not cause a forest transition in Ethiopia in the near future. The political-ecological and the neo-Boserupian perspectives are complementary in providing an appropriate framework for understanding forest cover changes in tropical mountains for the three historical time steps. The neo-Boserupian perspective interacts with the political-ecological context. In this perspective forest recovery is linked with increasing population growth, because increasing population densities stimulate innovations, which results in an intensification of land and resources use (De Haan, 2000). However, the neo-Boserupian framework fails to explain the secondary effect observed in the third time step. This secondary effect corresponds with aggravated deforestation in the afromontane forest after complete protection of the afro-alpine forest. The Boserup perspective is a liberal approach, whereas protection is a state intervention. Leach and Fairhead (2000) therefore propose a landscape-structuration perspective to understand nonlinear trajectories of population-forest dynamics. In this perspective, pathways of forest cover change are shaped by the interaction between population change and institutional and policy arrangements. This explains the observed secondary effect, due to complete protection of the afro-alpine forest. Subsequently, this indicates the need for a holistic management strategy for mountain forests.

Morales et al. (2004) question the traditionally used temperature limitation for tree growth at the treeline, since high transpiration rates prevail in tropical mountains (50-90% higher than in mid-latitude mountains (Leuschner, 2000)) which cause water shortage and impede tree growth. This is the case in the subtropical mountains of Northwestern Argentina characterized by dry conditions (<200 mm above 4000 m) (Morales et al., 2004). However, Bräuning (2009) observed the opposite relation in the humid mountain rainforest in southern Ecuador. Rainfall is thus expected to enhance tree growth under dry conditions and to impede tree growth under wet conditions. In the study area a negative correlation is expected but not significant (Chapter 9). In the growing season, a positive correlation with minimum temperature is observed (Chapter 9). Treelines are widely considered to be thermally limited (Harsch et al., 2009; Körner, 2007; Paulsen and Körner, 2014). In Chapter 8 (Figure 8.16) the potential climatic treeline elevation, based on air and soil temperature trends with elevation, is projected and corresponds with 4100 m a.s.l., which is 400 m higher than the current extent of the ericaceous belt. In the Simen Mountains, in local areas isolated from anthropo-zoogenic pressure, there is evidence for a treeline rise. At present, the treeline is located up to 4000 m a.s.l. and upper individuals up to 4050 m a.s.l., which is near to this potential climatic limit. Treeline migrations in the East African mountains during the LGM were also indicated to be primarily temperature driven (Saltré et al., 2013).

Yet, this mechanistic relation between air temperature and treeline elevation is a strong simplification of real vegetation dynamics. For example, the atmospheric CO_2 concentration was also indicated to have had an important impact on altitudinal shifts of the treeline in the LGM (Saltré et al., 2013). Higher atmospheric CO_2 concentrations could enhance growth through faster carbon fixation, as long as other factors such as water availability are not limiting (Hickler et al., 2008). The competitive balance between C_4 plants and C_3 plants (mainly tree species) also had an impact on the distribution of tropical forests in the LGM (Street-Perrott et al., 1997). In the future increased atmospheric CO_2 could favor C_3 tree species (Crawford, 2008). However, more research is required to better understand the effect of elevated atmospheric CO_2 on tree growth at the tropical altitudinal treeline.

11.5 General conclusions

Vulnerable tropical mountain forests provide important ecosystem services for surrounding communities and for biodiversity. At present, this fragile environment is subjected to biophysical and socio-economic drivers of change. Human induced land use and land cover changes have had an undeniable impact on natural vegetation. Local communities directly affect the forest cover for their subsistence, through wood harvesting, fire and livestock browsing. Mountain ecosystems are, according to UNESCO, among the most sensitive ecosystems in the world and the treeline, at the upper edge of the mountain forest, forms one of the most apparent vegetation boundaries worldwide. Treelines are temperature sensitive and thus potentially responsive to climate change. A multidisciplinary study of treeline dynamics has been conducted in three North Ethiopian mountains: the Simen Mts. (13°16’N, 38°24’E, 4540 m a.s.l.) home to the highest peak of Ethiopia (Ras Dejen Mt.); Lib Amba Mt. (12°04’N, 39°22’E, 3993 m a.s.l.) of the Abune Yosef Mts.; and Ferrah Amba Mt. (12°52’N, 39°30’E, 3939 m a.s.l.). The key research questions raised in this thesis state ‘Are treelines in the African highlands rising due to climate change?’ and more generally ‘How did the high altitude African tropical forests change over the last 50 years?’ The answer to these questions can be partly decomposed in sub-questions answered in the individual chapters.

Are treelines in tropical Africa rising? On average, the tropical African treeline is depressed below its climatic limit by 400 ± 300 meter, but regional differences are high and there are still many uncertainties. The main potentially determining factors of treeline dynamics in tropical Africa are temperature, precipitation and cloudiness, carbon balance, fire and anthropo-zoogenic impacts. In general, treelines in tropical Africa have been primarily driven by fire and anthropogenic pressure rather than climate change (Chapter 2).

Can we use periglacial depositis to reconstruct paleoclimatic conditions in the North Ethiopian Highlands? Based on periglacial deposists, a temperature drop around 6°C was calculated for the LGM in Ferrah Amba, Lib Amba, and in the Abuna Yosef range.

Moreover, small marginal glaciers are suggested to have existed in the LGM at the upper north-facing slopes of the Abuna Yosef range under local topo-climate conditions (Chapter 3).

What is the effect of protection on the physiognomy of the afro-alpine *Erica arborea* forest? Increased forest protection measures have proven successful at Lib Amba Mt., as indicated from a comparison between the physiognomy of the afro-alpine *Erica* forest between Ferrah Amba and Lib Amba. The heavily logged forest of Ferrah Amba is strongly disturbed with more than 50% of the trees damaged and a high amount of tree stumps (app. 30%). The forest is degraded to a dwarf forest with an average tree height below 2 m and a low canopy cover. Simultaneously, tree height is more than two meter and tree density and forest canopy are almost double in the lightly logged forest of Lib Amba. There is thus a high need for improved forest protection in Ferrah Amba Mt. in order to allow a natural recovery of the forest (Chapter 4).

Are the afromontane and afro-alpine forests decreasing over the past half century? The history of forest cover change is ‘opposite’ between the afromontane and afro-alpine forests in Lib Amba Mt. The afro-alpine forest declined between 1964 and 1982 and extended between 1982 and 2015, whereas, the afromontane forest was stable between 1964 and 1982 and strongly declined between 1982 and 2015. Complete closure of the afro-alpine forests in the most recent period (1982-2015) caused a secondary deforestation effect in the afromontane belt (Chapter 5 and 10).

Did the establishment of the National Park in the Simen Mountains affect forest cover? In the protected Simen Mountains National Park (SMNP) an increase of the forest cover was observed between 20 and 40%. But locally, continued anthropo-zoogenic pressure causes a continued decline of the forested area (-1.47% per decade) (Chapter 6).

Can we use RFE to estimate rainfall dynamics in the tropical African highlands? A local calibration of NOAAs RFEs showed major rainfall underestimations in areas with pronounced relief (Chapter 7).

How do microclimatic conditions influence *Erica arborea* tree growth at the treeline in the North Ethiopian highlands? Rainfall, air, ground and soil temperatures were measured in meteorological stations, installed along the slope of the mountain ranges. Rainfall does not show a significant trend with elevation. Rainfall follows a bimodal pattern with an unreliable small rainy season (March-May) preceding the main rainy season (June-September). The soil temperature is influenced by vegetation cover in winter and incoming radiation in summer. Soil temperatures (- 12 cm depth) in forested areas are on average 1.8°C colder in comparison to non-forested areas. This can cause a positive feedback effect by the forest, sheltering tree seedlings. Air temperature is strongly related with altitude. The average environmental lapse rate in the study area is 0.72°C per 100 m. Air temperature is indicated to be the dominant driver of the treeline limit in the North Ethiopian highlands. The treeline is currently located 400 m below its climatic potential limit and is expected to increase an extra 150 m under a climate warming of 1°C (Chapter 8).

Is *Erica arborea* growth responsive to climate variability? A 48 year *Erica arborea* tree-ring chronology was established and is positively correlated with minimum temperature in the growing season and negatively with minimum temperature in the azmera season. Rainfall is not significantly correlated with tree growth, but long-term high elevation rainfall data is needed to better understand the rainfall effect. Early azmera rainfall followed by a dry spell can cause the formation of IADFs in the tree rings (Chapter 9).

How did land use patters affect vegetation cover in the North Ethiopian highlands? A neo-Boserupian perspective of population-forest dynamics and a political-ecological model can be used to explain forest cover changes in the afro-alpine belt. The political-ecological transitions correspond well with afro-alpine forest cover changes in the study area; i.e. degrading conditions under late feudal and Derg regime (1970-1991) and improving environmental conditions under the Ethiopian People's Revolutionary Democratic Front (EPRDF) regime (after 1991). Following Boserupian theory, extensive land clearing (deforestation and degradation) prevails during human colonization under relatively low population densities (i.e. the period 1964-1982). When population pressure then rises, necessity drives farmers to invest in better land management and agricultural intensification which results in forest regeneration and an upwards shift of the treeline (i.e. the period 1982-2015). In the afromontane belt, population densities were already high in the first period (1965-1982), which corresponds with a period of stabilization of the forest (second phase in the neo-Boserupian framework) (Chapter 10).

These answers of the individual research questions allow answering the key questions. Are treelines in the African highlands rising due to climate change? Under the impact of population dynamics, the treeline in tropical afro-alpine mountains of North Ethiopia is primarily anthropo-zoogenic driven. Direct human disturbance and livestock browsing shape the spatial and temporal patterns of both the forest and the treeline. However, apart from this pressure effect, an upwards shift of the treeline could be observed in isolated areas (up to 245 m between 1966 and 2014) which is potentially related to changes in the mountain climate. Still, more research is required to further disentangle the relation between tree growth and climate variability.

The second key question about the history of the high altitude African tropical forests over the last 50 years is already fully answered in the above questions. In addition, to understand mountain forest dynamics over the past 50 years a conceptual model is presented in the thesis. This model integrates the history of forest cover, treeline dynamics and their drivers and at the same time projects future scenarios of the vegetation belts under different land management conditions. An integrated holistic strategy is projected to be most sustainable. In this approach, protection measures are foreseen in all successive vegetation belts at the same time, with special attention for forest growth at steep slopes and near to remaining remnant patches to enhance forest rehabilitation. Quick recovery of the northern forest in Lib Amba provides evidence that degraded forest vegetation would benefit rapidly from complete protection. Management interventions are therefore vital to restore the important ecosystem services of mountain forests.

11.6 Future research perspectives

In order to improve understanding of the interaction between mountain climate and *Erica* tree growth in Northern Ethiopia, or in the African tropical mountains, additional research is a requisite.

In this study, the complex relation between prevailing climate conditions and limitations of tree growth are mainly approached from a climate perspective. Exception is Chapter 9, in which tree growth is characterized from cambial marked stem disks. There remain many research questions on small-scale interactions between tree growth and climate variability. For example, repeated cambial pinning throughout the vegetation period could further enhance our insight in tree growth at the treeline. In combination with climate monitoring, this could reveal detailed tree growth-climate interactions (e.g. Schmitt et al. 2004). An important remaining research question is 'at what life stage is tree growth most sensitive to climate variability?' The majority of the treeline studies focus on tree life stages beyond seedling establishment, although the greatest mortality occurs to seedlings (Smith et al., 2009). Microclimatic facilitation for seedling establishment is of key concern for the formation of new forest. Ecophysiological studies of seedling establishment would thus greatly improve the understanding of tree growth at the treeline ecotone (Smith et al., 2009). In addition, field measurements in experimental settings could also help to further disentangle the ecophysical mechanisms of treeline altitude dynamics (e.g. Hättenschwiler et al. 2002). Such ecophysical studies on the effect of mountain climate conditions would strongly improve our understanding of spatial patterns of the afro-alpine treeline. Moreover on a local scale, the influences of soil biological, soil physical and soil chemical site conditions are important to explain spatial patterns, but are not sufficiently considered in the treeline debate (Holtmeier, 2009).

Repeat photography is proven valuable as a technique to study long-term treeline shifts in tropical Africa. A large amount of historical terrestrial photographs could improve the understanding of forest cover change and treeline dynamics in tropical Africa. Moreover, this could answer the question how the high altitude African tropical forest changed in the first part of the 20th century. Such historical landscape photographs are increasingly available in major archives and a growing number can be traced on the internet (Nyssen et al., 2014; Hoffman and Rohde, 2011; Webb et al., 2010).

Besides further research on treeline dynamics, improved understanding about the ecosystem services of afro-alpine forests is crucial to assess the potential effects of changes in the forest cover. This could help to answer the question whether the ecosystem services of the afro-alpine tropical mountains are under threat. Many authors discuss ecosystem services of mountain forests (e.g. Miehe and Miehe 1994; Aerts et al. 2002; Price 2003; Nyssen et al. 2004; Spehn and Liberman 2006), but relatively few have studied these (e.g. Markart et al. 2007).

11.7 Management recommendations of the afro-alpine forests

The prevailing forest conditions for different management strategies are shown in Figure 11.4. The completely protected forest of the northern slope of Lib Amba, with a high density of trees and a high canopy cover is shown in Figure 11.4A. In Figure 11.4B a remnant *Erica* forest is shown, with more than 4 m high *Erica* trees. This forest is condemned to disappear since there is no rejuvenation of the forest, due to very intensive livestock browsing. In Figure 11.4C and D, the heavily disturbed dwarf forest of Ferrah Amba is shown, severe anthropo-zoogenic pressure impede tree growth in this forest. From these examples it becomes clear that forest protection is necessary, excluding both livestock browsing and human disturbances.

Figure 11.4 *Erica* forests under different land management strategies: (A) Lib Amba Mt. northern forest under protection (20/07/2013); (B) Lib Amba Mt. southern slope remnant forest under strong livestock browsing pressure (17/02/2012); (C,D) Ferrah Amba Mt. dwarf forest under pressure by livestock browsing and human disturbances (20/11/2014; 6/10/2012)

A sustainable management strategy must be holistic, taking different vegetation belts in consideration at the same time, in order to avoid degradation in excluded areas. Simultaneously, in non-protected areas a slope and time specific grazing management must be introduced (Mwendera et al., 1997). Light and moderate grazing on gentle slopes can enhance productivity during the active growth period, but decrease sharply at very high grazing pressure, while grazing on steep slopes is most devastating for the vegetation cover (Mwendera et al., 1997). Moreover, forest cover on steep slopes is also important for slope stability. Therefore, it is recommended to primarily protect the steep slopes. This would not hinder tree growth, since *Erica* is reported to grow well on shallow soils (Egziabher, 1988; Chapter 4). Protected areas must be installed in the vicinity of remnant forests for enhanced forest recovery. Such protection measures are ideally combined with a new function for the closed area. In this regard, the spectacular mountain environment and the endemic wildlife species of the Ethiopian highlands form an important asset for the attraction of tourists. Ecotourism with community participation, if well organized, can provide local economic benefits while rehabilitating the ecosystem and can create conservation attitude and behavior within the local communities (UNEP, 2002). At the slope of Lib Amba Mountain a tourist lodge has been recently constructed to attract tourists hiking in the Abune Yosef Mountains. However, participation of the local communities should be enhanced to create more economical and environmental benefits from tourism.

In addition, a switch from traditional biomass to renewable energy sources would reduce forest dependency of the local communities. The International Energy Agency estimated that 80% of the people in Africa South of the Sahara rely on traditional biomass fuel for cooking, e.g. firewood, charcoal, animal dung (IEA, 2010). In Ethiopia, there have been very large investments in renewable energy over the past decades, with the Grand Ethiopian Renaissance Dam as flagship. But alternatives for traditional biomass fuels in rural areas are lagging behind (Wolde-Ghiorgis, 2002). The continued use of biomass fuels does not only affect the forest, but also affects human health and food security (Gwavuya et al., 2012). However, due to the prevailing mountain climate traditional renewable sources of energy are not efficiently applicable; it is too cold for biogas and there is too much cloudiness in the rain season for efficient use of solar cookers. Alternatively, fuel efficient stoves could be introduced to reduce the pressure on the afro-alpine forests (Karekezi and Turyareeba, 1995). Such improved stoves are indicated to significantly increase the heat transfer while cooking and are available at a low-cost (MacCarty et al., 2010). The problem is that these traditional stoves are also important as a source of heat during the cold evenings. Overall, the introduction of green electricity is probably the best alternative source of energy to strongly reduce forest pressure.

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Nederlandse samenvatting

Boomgrensdynamiek en veranderingen in het bosareaal in het afro-alpiene hoogland van Ethiopië, zoals beïnvloed door klimaatsveranderingen en antropo-zoögene invloeden.

Hoofdstuk 1 – Algemene inleiding

Berggebieden maken deel uit van de meest gevoelige ecosystemen in de wereld (Price en Egan, 2014) en zijn tegelijkertijd regionaal en globaal belangrijk door hun ecologische, socio-economische en esthetische waarde (Schild, 2008). De belangrijkste ecosysteemfuncties van bergen zijn drievoudig: bevoorradende functies, regulerende en ondersteunende functies en culturele functies (Körner en Ohsawa, 2005). Bovendien spelen de vegetatie- en bodemkarakteristieken in berggebieden een belangrijke rol voor de reductie en mitigatie van natuurlijke risico's (IPCC, 2007). Het waterhoudend vermogen van bosvegetatie in berggebieden is belangrijk voor de regulatie van de hydrologische balans (Körner en Ohsawa, 2005). Er bestaan schattingen dat bijna de helft van de wereldbevolking direct of indirect afhankelijk is van wateropbrengsten uit berggebieden (Messerli, 2004).

Op dit moment zijn deze kwetsbare berggebieden onderhevig aan een reeks biofysische en socio-economische drijfveren voor verandering, inclusief klimaatsveranderingen. Veranderingen in het ecologisch evenwicht bedreigen de ecosysteem functies van berggebieden en stellen lokale en regionale gemeenschappen bloot aan biofysische en socio-economische risico's. Ondanks toegenomen aandacht voor het ecologisch evenwicht in berggebieden op de internationale agenda (Schild, 2008), bestaat er weinig wetenschappelijk onderzoek over afro-alpiene bossen in het tropisch Afrikaans hoogland. Deze bossen in het tropisch hoogland zijn nochtans belangrijk voor stabiliteit van de berghelling en regionaal als een hygrische buffer (Miehe en Miehe, 1994; Price, 2003). Bossen in berggebieden spelen een belangrijke rol voor het opvangen en opslaan van neerslag, voor het reguleren van oppervlakkige afstroom van water, het reduceren van bodemerosie en als bescherming tegen overstromingen, aardverschuivingen en steenval (Aerts et al., 2002; Miehe en Miehe, 1994). Deze berggebieden zijn ook belangrijk als biotoop voor biodiversiteit; in het bijzonder in het Noord Ethiopische hoogland is de endemische soortenrijkdom groot.

De gemiddelde wereldwijde temperatuur is gestegen tijdens de laatste eeuw, een verandering die in het bijzonder voelbaar is op grote hoogte en hoge latitude. In deze context van klimaatsveranderingen, is er nood aan extra kennis over deze kwetsbare bossen in het tropische hoogland. De boomgrens ecotone is temperatuurgevoelig en dus potentieel beïnvloed door de opwarming van het klimaat (Holtmeier en Broll, 2007). Het aantal studies met betrekking tot de boomgrensdynamiek in de tropen neemt toe (Bijv. Bader, 2007; Wesche et al., 2008; Sassen et al., 2013), maar de tropische boomgrens blijft relatief weinig bestudeerd in vergelijking met studies naar boomgrensdynamiek op noordelijke latitudes (Holtmeier en Broll, 2007).

De primaire doelstelling van dit proefschrift is om boomgrensdynamiek en veranderingen in het afro-alpiene bosareaal in Noord Ethiopië sinds het midden van de twintigste eeuw te bevatten. Algemeen worden volgende twee onderzoeksvragen gesteld:

- Is de boomgrens in het tropisch Afrikaans hoogland aan het opschuiven naar boven ten gevolge van klimaatsveranderingen?
- Hoe is het afro-alpiene bosareaal in tropisch Afrika veranderd over de laatste 50 jaar?

Deze kernvragen werden opgedeeld in sub-vragen, beantwoord in de individuele hoofdstukken:

- Is de boomgrens in het tropisch Afrikaans hoogland aan het opschuiven? (Hoofdstuk 2)
- Kunnen periglaciale afzettingen gebruikt worden om paleoklimatologische condities te reconstrueren in het Noord Ethiopische hoogland? (Hoofdstuk 3)
- Wat is het effect van beschermingsmaatregelen op de fysiognomie van het afro-alpiene *Erica arborea* bos? (Hoofdstuk 4)
- Zijn de afromontane en afro-alpiene bossen afgenomen tijdens de afgelopen halve eeuw? (Hoofdstuk 5 en 10)
- Heeft de vestiging van het Nationaal Park in het Simen gebergte een invloed gehad op het bosareaal? (Hoofdstuk 6)
- Kunnen “Rainfall Estimates” (RFE) gebruikt worden om neerslagpatronen te bestuderen in the tropisch hoogland van Afrika? (Hoofdstuk 7)
- Hoe beinvloeden microklimaatsomstandigheden de groei van *Erica arborea* bomen aan de boomgrens in het Noord Ethiopisch hoogland? (Hoofdstuk 8)
- Is de groei van *Erica arborea* bomen gevoelig voor klimaatsveranderingen? (Hoofdstuk 9)
- Wat is het effect van landgebruikspatronen op vegetatieverandering in het Noord Ethiopisch hoogland? (Hoofdstuk 10)

Het studiegebied bestaat uit drie berggebieden in het Noord Ethiopisch hoogland. Het Simen gebergte (13°16’N, 38°24’E, 4540 m), Lib Amba (12°04’N, 39°22’E, 3993 m) deel van het Abuna Yosef massief en Ferrah Amba (12°52’N, 39°30’E, 3939 m). Deze drie bergen hebben een piek boven de huidige *Erica* vegetatie zone tussen 3200 en 3700 m boven het zeeniveau.

Referenties zie hoofdstuk 1

Deel 1

In Deel 1 van dit proefschrift worden (i) de stand van zaken met betrekking tot boomgrensdynamiek in het tropisch Afrikaans hoogland en (ii) de ecologische context van het studiegebied besproken in drie hoofdstukken.

Hoofdstuk 2 – Boomgrensdynamiek in het tropisch Afrikaans hoogland: het identificeren van drijfveren en veranderingen

Afro-alpiene bossen verzorgen belangrijke ecosysteemdiensten in het kwetsbaar milieu van het tropisch hoogland. De temperatuurgevoelige boomgrens is potentieel belangrijk als proxy voor klimaatsveranderingen in de tropen. In dit hoofdstuk worden de factoren geëvalueerd die een potentiële invloed hebben op de boomgrens in het tropisch hoogland. Ondanks recente temperatuurstijgingen is de boomgrens niet gestegen in het tropisch Afrikaans hoogland. Dit komt door een sterke menselijke impact die zorgt voor een stabilisatie en zelfs een verlaging van de boomgrens, onder de natuurlijke klimatologische grens. De belangrijkste drijfveren voor verandering zijn voornamelijk vegetatiebranden en antropo-zoögene druk, begrazing in het bijzonder. Lange perioden van droogte kunnen een “trigger” vormen voor ontbossing ten gevolge van vegetatiebranden en een verlaging van de boomgrens. Ook vulkanische activiteit kan een potentiële invloed hebben op de boomgrens in vulkanische gebieden. In het algemeen beschouwd, kan de boomgrens dus niet gebruikt worden als een proxy voor klimaatsveranderingen in het tropisch Afrikaans hoogland.

Hoofdstuk 3 - Geomorfologie en paleoklimatologische significantie

Geomorfologisch onderzoek en een detailkartering van huidige en historische peri(glaciale) landvormen is noodzakelijk om de impact van klimaatanomalieën te begrijpen. De Ethiopische hooglanden tonen een grote variatie in het hedendaagse en historische klimaat en dus in het voorkomen van glaciale en periglaciale landvormen. Desalniettemin zijn slechts enkele berggebieden bestudeerd en bestaan er geen gedetailleerde karteringen. Om een gedetailleerde reconstructie toe te laten van de impact van historische glaciale activiteit op de geomorfologie, de vegetatie en van de temperatuurs-anomalieën werd een gedetailleerde geomorfologische kaart opgesteld voor drie berggebieden: Ferrah Amba, 12°51’N 39°29’E; Lib Amba, 12°04’N 39°22’; en Abuna Yosef, 12°08’N 39°11’E. In alle drie de berggebieden werden inactieve solifluctielobben teruggevonden die naar alle waarschijnlijkheid gedateerd kunnen worden naar het Laatste Glaciale Maximum (LGM). In de omgeving van de hoogste piek, de Abuna Yosef piek, werden drie plaatsen met potentieel morenemateriaal van een kleine laat Pleistocene gletsjer geobserveerd. Deze marginale gletsjers kwamen voor onder de gemodelleerde sneeuwlijn, onder lokale topografische-klimatologische micro-omstandigheden. Bewijs voor het voorkomen van lawine-gevoede gletsjers in Ethiopië (en Afrika) is nog niet eerder gepubliceerd. De huidige vorstactie is gelimiteerd tot vorstbarsten en kleinschalige polygonale vorststructuren. Veranderingen in de hoogtegrens voor periglaciale en glaciale processen tijdens de laatste koude perioden werden bestudeerd aan de hand van het voorkomen van periglaciale en glaciale landvormen. De depressie van glaciale en periglacial hoogtezone met bij benadering 600 m komt overeen met een temperatuurdaling van 6°C tijdens de Laat Glaciale periode. Deze studie vormt een voorbeeldstudie voor alle intermediaire berggebieden (3500-4200 m) in het Noord Ethiopisch hoogland.

Hoofdstuk 4 – Fysiognomie van de afro-alpiene bossen onder verschillende groeicondities in het Noord Ethiopisch hoogland

In het algemeen is bosmanagement in Afrika ten zuiden van de Sahara gelimiteerd door onvoldoende kennis over de conditie en structuur van de bossen. In dit hoofdstuk, wordt de status en structuur van de *Erica arborea* boomgrens bestudeerd onder verschillende condities in het Noord Ethiopisch hoogland. Een vergelijking wordt gemaakt tussen (i) minimaal gekapte bossen in Lib Amba en maximaal gekapte bossen in Ferrah Amba en (ii) de groei van bomen centraal in het bos en aan de aan stress blootgestelde boomgrens. De status van het bos wordt beschreven aan de hand van een verkennend onderzoek in verschillende plots. In deze plots worden verschillende parameters van de bomen opgemeten en gebruikt voor het berekenen van de dekkingsgraad van het bladerdak, het grondvlak, de hoogte-diameter-coëfficiënt en de kroon ratio. De structuur van de boomgrens werd geanalyseerd aan de hand van transect-metingen doorheen de boomgrens ecotone en door een sigmoïdale functie te plotten doorheen de relatie tussen de hoogte van de boom en de hoogte op de berghelling. Dit verkennend onderzoek toont aan dat het bos in Ferrah Amba sterk verstoord is, een groot aandeel van de bomen zijn gekapt (ca. 30%)

en meer dan 50% van de bomen zijn beschadigd. De dekkingsgraad van het bladerdak is laag en de gemiddelde boomhoogte is lager dan twee meter. Dit is het resultaat van continue antropo-zoögene druk, die ervoor gezorgd heeft dat het bos in Ferrah Amba gedegradeerd werd tot een dwerg-bos. Daarentegen, hebben de beschermingsmaatregelen in Lib Amba een succesvol effect op de status van het bos. De gemiddelde boomhoogte is er meer dan twee meter, de boomdensiteit is bijna dubbel en de bedekkingsgraad van het bladerdak is meer dan 50%. Op de boomgrens komen er meer *Erica* bomen voor op solifluctielobben dan in de nabijgelegen depressies, ten gevolge van competitie. Deze studie toont de nood aan voor betere beschermingsmaatregelen in Ferrah Amba, in het bijzonder op steile hellingen, om zodoende een natuurlijk herstel van het bos te bevorderen. Het herstel van dit afro-alpiene bos is belangrijk voor de verderzetting en verbetering van de vitale ecosysteemdiensten die het bos verzorgt.

Deel 2

In Deel 2 van dit proefschrift worden de veranderingen in het bosareaal en de boomgrens bestudeerd voor twee voorbeeldstudies, op basis van luchtfoto's, historische landschapsfoto's en satellietbeelden.

Hoofdstuk 5 – Afro-alpiene boomgrensdynamiek en afromontane veranderingen van het bosareaal sinds het begin van de twintigste eeuw: Lib Amba

Hoog-alpiene bossen zijn belangrijk voor het levensonderhoud van lokale gemeenschappen in het kwetsbare milieu van de dichtbevolkte tropische hooglanden. Desondanks heeft de mens een directe impact op de ecosysteemfuncties van bossen door de graasdruk van veeteelt, vegetatiebrand en houtkap. De temperatuurgevoelige boomgrens is weinig onderzocht in de tropen in vergelijking met boomgrenzen op hogere noordelijke latitudes. In deze studie wordt de *Erica arborea* boomgrens bestudeerd in Lib Amba (12°04'N, 39°22'E, 3993 m) deel van het Abune Yosef massief in het tropisch hoogland van Noord Ethiopia. De huidige boomgrens en het bosareaal werd gekarteerd op basis van hoge resolutie satellietbeelden van Google maps en veldgegevens (2010-2013), terwijl het historische bosareaal gekarteerd werd op basis van luchtfoto's (1965-1982) en herhalingsfotografie (1917-2013). De luchtfoto's en satellietbeelden werden geometrisch gerectificeerd en geclassificeerd in bos/niet-bos binaire kaarten. De binaire bos lagen werden vervolgens gebruikt om veranderingen in het bosareaal en in de boomgrens te detecteren aan de hand van beeldvergelijking tussen de drie tijdslagen (1965-1982-2010). Deze kaartenlagen en de herhalingsfoto tonen aan dat er twee periodes waren van ontbossing (1917-1965 en 1982-2013), terwijl het bosareaal stabiel was tussen 1965 en 1982. In het bijzonder in de periode tussen 1982 en 2010 was er een sterke ontbossing van het bosareaal, geassocieerd met een bescherming van het afro-alpiene bos en een toename van de bevolking van 77 tot 153 inwoners per vierkante kilometer. Er is significant bewijs dat de *Erica arborea* boomgrens gestegen is met 7 tot 15 verticale meter tussen 1965 en 2010, in een gebied met dalende antropo-zoögene druk.

Hoofdstuk 6 – Landgebruiksveranderingen in het Simen gebergte (Ethiopië), een halve eeuw na de oprichting van het Nationaal Park

Het Simen gebergte herbergt verschillende bedreigde en inheemse wilde dieren en biedt verschillende belangrijke ecosysteemdiensten. Maar ondanks het regionale ecologische belang, werd het Simen gebergte opgenomen in de lijst van het bedreigde Werelderfgoed sinds 1997. Dit leidde tot de noodzaak voor een evaluatie van landschapsveranderingen in het Simen gebergte. Landschapsveranderingen werden bestudeerd van voor de oprichting van het Nationaal Park in het Simen gebergte in 1969, met behulp van historische terrestrische landschapsfoto’s (1966-2009). Herhalingsfoto’s werden genomen in 2014 en geanalyseerd aan de hand van een expert rating systeem met acht correspondenten. Een toename van het bos werd geobserveerd in de omgeving van Sankaber en Imet Gogo (20-40%). Maar in de omgeving van Gich is het bosareaal afgenomen met een snelheid van -1.41% per decade. Er is geen significant effect ($p>0.05$) van de grens van het Nationaal Park op veranderingen in de houtige vegetatie, door een continue antropo-zoögene druk in het Nationaal Park. De snelheid van verandering wordt ook niet beïnvloed door andere biofysische (hoogte) of sociale factoren (afstand tot scout kampen). Maar, de densiteit van huizen binnen een straal van 2.2 km, als een proxy voor de menselijke druk, verklaart 32% van de ruimtelijke variatie van de afname in houtige vegetatie ($p<0.05$). Zes herhalingsfoto’s tonen een stijging van de boomgrens met meer dan 1 m per jaar in gebieden met een lage antropo-zoögene druk. Dit is potentieel gerelateerd met een opwarming van 1.5°C over de afgelopen 50 jaar. In het algemeen is een verdere afname van de antropo-zoögene druk noodzakelijk om een natuurlijk herstel van de afro-alpiene vegetatie toe te laten en de habitat van de bedreigde wilde dieren te herstellen in het Simen gebergte.

Deel 3

In Deel 3 van dit proefschrift worden de belangrijkste drijfveren voor veranderingen in het afro-alpiene bosareaal en in de boomgrens bestudeerd aan de hand van multidisciplinaire methoden.

Hoofdstuk 7 – Evaluatie van spatio-temporele neerslag variabiliteit in een tropisch berggebied (Ethiopië) op basis van NOAAs satelliet afgeleide neerslag schattingen (RFE)

Seizoensgebonden en jaarlijkse variatie in neerslag kan enorme economische schade veroorzaken voor lokale landbouwers en veehouders, niet alleen vanwege beperkte totale neerslaghoeveelheden, maar ook vanwege lange droge perioden tijdens het regenseizoen. Het semi-droge tot subhumide bergklimaat van het Noord Ethiopisch hoogland is bijzonder kwetsbaar voor variabiliteit in neerslag. In dit hoofdstuk, worden spatio-temporele neerslagpatronen geanalyseerd op een regionale schaal in het Noord-Ethiopisch hoogland met behulp van satelliet-afgeleide neerslag schattingen (RFE). Omdat er een zwakke correlatie bestaat in het droge seizoen, tussen de RFE en de neerslag gemeten in de Meteorologische Stations (MS), wordt enkel de regenval van maart tot september gebruikt, verantwoordelijk voor ca. 91% van de jaarlijkse neerslag. Een lokale kalibratie van de RFE data met neerslagstationsgegevens werd gevalideerd als techniek om de neerslagsvoorspelling van RFE te optimaliseren in een regionaal bergachtig studiegebied. Hellingsgradiënt, hellingsoriëntatie en hoogte hebben geen significante meerwaarde voor een lokale kalibratie van de RFE. De schatting van de maandelijkse neerslag verbeterde met gemiddeld 8% op basis van het kalibratiemodel. Gebaseerd op het kalibratiemodel konden jaarlijkse neerslagkaarten en een gemiddelde isohyetenkaart voor de periode 1996-2006 opgesteld worden. Hellingsgradiënt, hellingsorientatie, hoogte, noordwaarde en oostwaarde werden geëvalueerd als verklarende factoren voor de ruimtelijke variabiliteit van de jaarlijkse neerslag in een stapsgewijze meervoudige regressie met het gekalibreerde gemiddelde van RFE 1.0 als afhankelijke variabele. De oostwaarde en noordwaarde hebben een significante invloed op de ruimtelijke spreiding van de neerslag (R2: 0,86), met de oostwaarde als belangrijkste factor (R2: 0,72). De spreiding rond de individuele trendlijnen van oostwaarde en noordwaarde vertonen een stijging van de neerslag variabiliteit in de drogere gebieden. De verbeterde schatting van de spatio-temporele variabiliteit van neerslag in een bergachtig gebied van RFEs is waardevol als input voor een breed scala aan wetenschappelijke modellen, maar neerslag in het zuidelijke bergachtige deel van het studiegebied blijft onderschat.

Hoofdstuk 8 – Microklimaat condities voor *Erica arborea* groei aan de boomgrens in het Noord Ethiopisch hoogland

Microklimaat condities in het tropisch Afrikaans hoogland zijn bepalend voor de groei van de vegetatie en het afro-alpiene bos aan de boomgrens. In dit hoofdstuk, worden de bepalende factoren van het microklimaat in berggebieden bestudeerd voor de afro-alpiene *Erica arborea* boomgrens voor twee bergketens in Noord-Ethiopië: Lib Amba, deel van het Abune Yosef massief, en Ferrah Amba. Neerslag, lucht-, grond- en bodemtemperatuur werd gemeten tussen maart 2012 en oktober 2014 in lokale meteorologische stations geïnstalleerd langs de helling van deze bergketens. Neerslag en grond- en bodemtemperatuur hebben geen significante relatie met de hoogte. Neerslag volgt een bimodaal neerslagpatroon met een onbetrouwbaar klein regenseizoen (maart-mei) voorafgaand aan het regenseizoen (juni-september). De bodemtemperatuur wordt beïnvloed door de vegetatie en de inkomende straling. De bodemtemperatuur (op -12 cm) in beboste gebieden is gemiddeld 1,8 °C kouder in vergelijking met niet-beboste gebieden. Dit kan een positief feedback effect veroorzaken door het bos, omdat de beschuttende zaailingen in het bos beschermd zijn tegen dagelijkse fluctuaties in de bodemtemperatuur. Luchttemperatuur is sterk gerelateerd met de hoogte. De gemiddelde verticale temperatuurgradiënt in het studiegebied is 0,72 °C per 100 m. De lucht temperatuur werd aangeduid als de belangrijkste limiterende factor voor de boomgrens in het Noord Ethiopisch hoogland. De boomgrens ligt momenteel 400 meter onder de klimatologische potentiële limiet en zal naar verwachting 150 m stijgen in associatie met een klimaatsopwarming van 1 °C.

Hoofdstuk 9 – De reactie van de groei van *Erica arborea* op klimaatveranderingen in het afro-alpiene tropische hoogland van Noord-Ethiopië

De belangrijke ecosysteemdiensten van de afro-alpiene tropische *Erica arborea* bossen staan onder toenemende ecologische en menselijke druk. De *Erica* boomgrens ecotone in het Ethiopisch hoogland vormt een temperatuursgevoelige vegetatiegrens, die potentieel getroffen wordt door klimaatveranderingen. Het cambium van tien *Erica arborea* bomen uit Lib Amba werd gemarkeerd in 2012 en bemonsterd na 498 dagen. Microfoto's van deze cambiale markeringen bevestigen de vorming van jaarringen (0,76 ± 0,24 mm) met een hogere dichtheid van de vaten in het vroeghout en radiaal afgevlakte vezels in de laatste lagen van het laathout. In-continuüm metingen van de grootte en dichtheid van de vaten op microfoto's tonen de vorming van inter-jaarlijkse dichtheidsfluctuaties (IADFs) aan, gerelateerd met vroege regenval in de periode maart-mei. Dezelfde stamschijven en 40 boorkernen werden gebruikt voor een gedetailleerde analyse van de groeiringen, met als resultaat een groeiring-chronologie met 18 bomen voor de periode 1966-2014. Een significant ($p < 0{,}1$) positieve correlatie met de minimumtemperatuur in het groeiseizoen (augustus) en een negatieve correlatie met de minimumtemperatuur in het Azmera seizoen (maart) werden aangetoond als de belangrijkste regulerende klimaatfactoren voor de groei van *Erica* bomen in het afro-alpiene bos. De aanwezigheid van jaarlijkse boomringen en de aangetoonde chronologie, geven de mogelijkheden voor groeiring analyses van *Erica arborea* aan alsook hun link met klimaatveranderingen in het afro-alpiene tropische hoogland.

Hoofdstuk 10 – Landgebruik en landbezettingsveranderingen sinds 1964 in de afro-alpiene vegetatiegordel van Noord Ethiopië

De mens heeft een belangrijke impact op het landschap, door veranderingen in landgebruik en landbedekking (LGB). Deze veranderingen vormen een bedreiging voor de kwetsbare ecosysteemdiensten van de tropische afro-alpiene vegetatie. Verschillende LGB verandering studies zijn beschikbaar voor het Ethiopisch hoogland, maar er is relatief weinig bekend over LGB verandering in de afro-alpiene zones. In dit hoofdstuk werden LGB veranderingen tussen 1964 en 2012 in kaart gebracht voor de afro-alpiene zone van Lib Amba, deel van het Abune Yosef massief in Noord-Ethiopië. Het historische LGB werd afgeleid van gegeorefereerde luchtfoto's van 1964 en 1982, en het huidige LGB (2012) van Bing Map satellietbeelden. Op basis van deze opeenvolgende LGB kaarten werden een tijdsdiepte kaart, LGB proporties, LGB transitie matrices en LGB veranderingstrajecten berekend. Twee belangrijke fases van LGB verandering zijn te onderscheiden, gekoppeld aan het “neo-Boserup perspectief”. (i) Tussen 1964 en 1982 was er een grootschalige ontbossing en algemene degradatie van de vegetatie boven de 3500 meter, in een periode van lage bevolkingsdruk; (ii) Tussen 1982 en 2012, was er een intensivering van het landgebruik gepaard met een licht herstel van de vegetatie en de *Erica arborea* bossen, onder verhoogde druk van de bevolking. Diepte-interviews hebben aangetoond dat lokale en gouvernementele beheermaatregelen belangrijk zijn als bescherming tegen degradatie van de vegetatie en uitputting van de bodem. Een succesvol herstel van het bos op Lib Amba biedt vertrouwen dat gedegradeerde afro-alpiene gebieden in een korte tijd kunnen herstellen onder volledige bescherming, in de nabijheid van resterende natuurlijke afro-alpiene vegetatie. Management interventies zijn dus van vitaal belang om de belangrijke ecosysteemdiensten van de afro-alpiene vegetatie te herstellen.

Deel 4

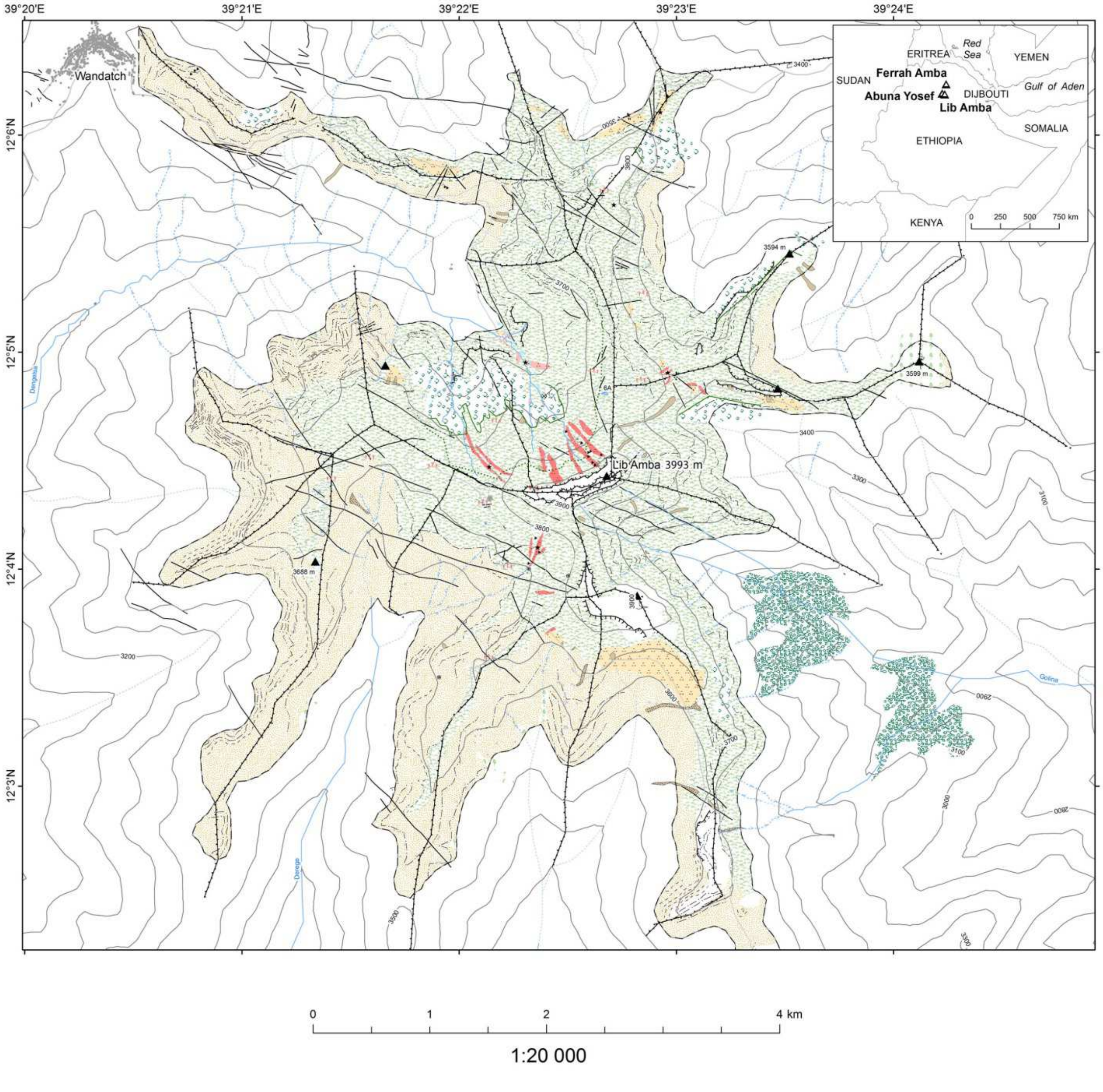
In Deel 4 van dit proefschrift wordt een algemeen conceptueel model voorgesteld dat veranderingen in de afro-alpiene vegetatie in het Noord Ethiopisch hoogland helpt begrijpen en worden de belangrijkste resultaten besproken.

Hoofdstuk 11 – Algemene discussie en besluit

De belangrijkste resultaten werden gebundeld in een algemeen conceptueel model voor veranderingen van de boomgrens en het bosareaal in het tropisch Afrikaans hoogland. Een neo-Boserup en politiek-ecologisch perspectief worden gecombineerd voorgesteld als belangrijkste drijfveren van verandering van het bosareaal. Het conceptueel model geeft een verklaring voor de historische veranderingen van de boomgrens en het bosareaal sinds 1964 en biedt 3 verschillende toekomstige scenario’s onder diverse beheersvormen van non-beheer tot volledige bescherming van het bos. Het model werd succesvol gevalideerd aan de hand van een voorbeeldstudie: het Guna gebergte. Desondanks zijn er verschillende beperkingen aan het model: beperkte periodieke data, geen bos transitie scenario, te veel nadruk op een temperatuur gelimiteerde boomgrens. De opgedeelde onderzoeksvragen uit hoofdstuk 1 werden beantwoord in de verschillende individuele hoofdstukken. Deze antwoorden laten toe om de twee hoofdvragen van het onderzoek te beantwoorden. (i) Zijn boomgrenzen in het Afrikaans hoogland gestegen ten gevolge van klimaatveranderingen? Onder invloed van een sterke en stijgende bevolkingsdruk op het landschap, is de boomgrens in het tropisch afro-alpiene gebergte van Noord-Ethiopië niet gestegen. Integendeel, de boomgrens is, in het algemeen, antropo-zoögeen gedreven en gelimiteerd onder de natuurlijke klimatologische grens. Rechtstreekse menselijke verstoring en begrazing door veeteelt vormen de ruimtelijke en temporele patronen van het bosareaal en de boomgrens. In geïsoleerde gebieden, beschermd tegen deze bevolkingsdruk, is er een opwaartse verschuiving waargenomen van de boomgrens (tot 245 m tussen 1966 en 2014), die potentieel samenhangt met veranderingen in het bergklimaat. Meer onderzoek is noodzakelijk om de relatie tussen boomgroei en de variabiliteit van het klimaat beter te begrijpen. (ii) Hoe is het afro-alpiene bosareaal in tropisch Afrika veranderd over de laatste 50 jaar? Twee fasen van vegetatieveranderingen kunnen worden onderscheiden voor de afro-alpiene vegetatiegordel. Een periode van ontbossing en degradatie tussen 1964 en 1982 en een periode van stabilisatie en herstel van het natuurlijk bos tussen 1982 en 2015. De onderliggende afromontane bosgordel heeft een tegengestelde verandering doorgemaakt, ten gevolge van het secundair ontbossingseffect. De drijfveren voor deze veranderingen kunnen begrepen worden binnen een politiek-ecologisch context en een neo-Boserup perspectief. Een geïntegreerde holistische beheersaanpak is vitaal voor het behouden en herstellen van de belangrijke ecosysteemdiensten die geleverd worden door de afro-alpiene bossen.

Appendix A

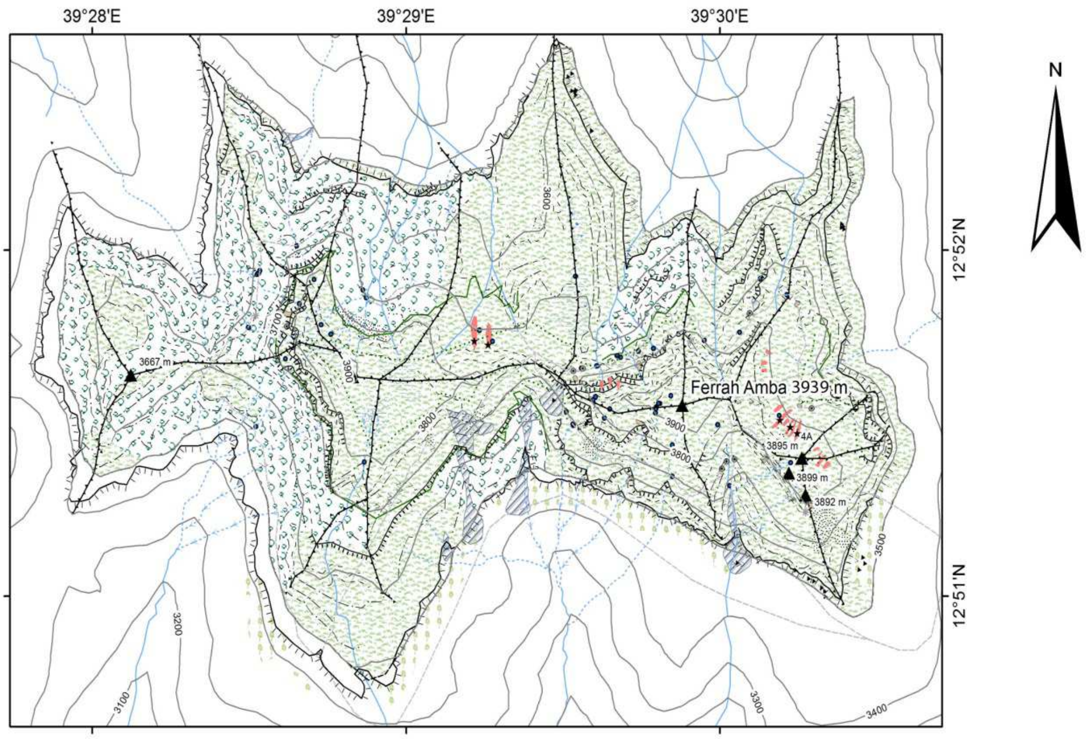
Appendix A contains the Geomorphological map of Chapter 3 with focus on glacial and periglacial landforms, subdivided in three sheets: Lib Amba Mountain, Ferrah Amba and Abune Yosef Mountains and the geomorphological legend.

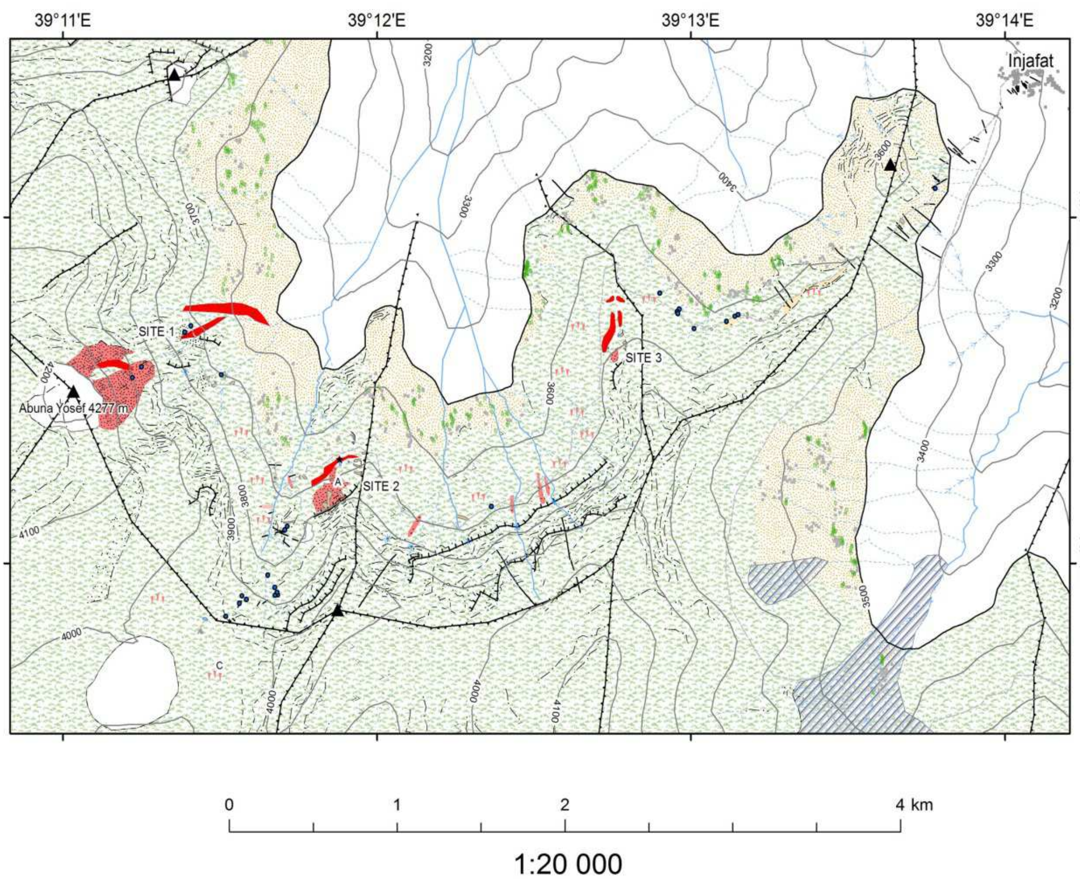


WGS_84_World_Mercator
Projected Coordinate System: UTM 37N
Prime Meridian: Greenwich (0,0)
Datum; D_WGS_84
100 meter contour line spacing
Detailed geomorphological map concerns only areas above 3500 m a.s.l..

ASTER DEM data, Nasa Earth Data
Topographic maps: Lalibela, Muja, Maychew, Bora. Ethiopian Mapping Agency
Aerial Photographs 1980, ET2, ETH2. SWEDSURVEY

Geomorphological field survey (04/07/2013 - 18/09/2013)
and mapping, cartographic work and map design performed by H. Hendrickx.
Faculty of Sciences, Department of Geography, Ghent University, Belgium


39°28'E
39°29'E
39°30'E
12°52'N
12°51'N
N
3667 m
Ferrah Amba 3939 m
3895 m
3899 m
3892 m
4A
3700
3800
3900
3600
3500
3200
3100
3300
3400


39°11'E
39°12'E
39°13'E
39°14'E
12°9'N
12°8'N
Injafat
SITE 1
SITE 2
SITE 3
Abuna Yosef 4277 m
A
C
3200
3300
3400
3500
3600
3700
3800
3900
4000
4100
0
1
2
4 km
1:20 000

PROCESSES/GENESIS

RED	Glacial
CORAL RED	Periglacial
PINK	Fluvio-periglacial
BLUE	Hydrology
GREEN	Vegetation
BLACK	Contours and structural geomorphology
GREY	Anthropogenic

MATERIAL

Bedrock

Volcanic rock outcrop

Post-LGM deposits

Large rockfall
Large dense rockfall
Small rockfall
Small dense rockfall
Debris fan
Landslide

Past deposits

Glacial and periglacial features

Moraine material
Solifluction lobe
Fluviosolifluction
Buried periglacial rubble
Scree slope

MORPHOGRAPHY/MORPHOMETRY

Contour (i. 100 m)
s Summits
Crest line
Dyke

Structural escarpment

Very distinct
Distinct
Vague
Partly buried

Contemporary periglacial features

Micro patterned ground

HYDROLOGY

Waterfall
Spring
Permanent stream
Ephemeral stream
Gully
Marshy area
Ephemeral lake

VEGETATION

Afro-Alpine grassland
Alpine forest (Erica)
Sub-Alpine forest (Juniper)
Eucalyptus

Tree line

Physiognomic tree line
Erica upper species limit

ANTHROPOGENIC

Housing
Tourist hut
Meteo station
Locally maintained spring
Spring with construction
Water adduction
Profile analyses

Roads

Primary road
Secundary road
Footpath

Land use

Cultivated land

Supplementary material to:
Hendrickx et al. "Glacial and periglacial geomorphology
and its paleoclimatological significance
in three North Ethiopian Mountains,
including a detailed geomorphological map."
Geomorphology, 2015

Miró Jacob (°1987, Ghent) is specialized in Physical geography at the Geography Department of Ghent University (Belgium). He obtained his master's degree in Geography in 2010 and his specific teachers' degree in 2011. In September 2011, he started his PhD focussed on forest cover change and treeline dynamics in the afro-alpine zone of the north Ethiopian highlands. The results, presented in this book, are based on several months of fieldwork in the upper highlands of North Ethiopia. The history of the high altitude afro-alpine forest is reconstructed for the past half century and the responsiveness of the treeline to climate change is questioned, using a multi-disciplinary method. Miró has presented his research at various (inter)national conferences and is the author of several international publications.

Erica arborea L.

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