Vegetation Diversity and Distribution Along the Bale Mountains Afroalpine Hotspot of Biodiversity in the Face of a Fast-Changing World

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Von

Herrn Yohannes Kidane Ogubamichael

geboren am 11/03/1971 in Asmara, Eritrea

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Amtierender Dekan: Prof. Dr. Benedikt Westermann

Prüfungsausschuss: Prof. Dr. Carl Beierkuhnlein (Erstgutachter)
Prof. Dr. Cyrus Samimi (Zweitgutachter)
Prof. Dr. Thomas Köllner (Vorsitz)
Prof. Dr. Sigrid Liede-Schumann

"A person with ubuntu is open and available to others, affirming of others, does not feel threatened that others are able and good, for he or she has a proper self-assurance that comes from knowing that he or she belongs in a greater whole and is diminished when others are humiliated or diminished when others are tortured or oppressed, or treated as if they were less than who they are."

Rev. Desmond Tutu

Dedicated to:

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Table of Contents

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Summary

Mountain ecosystems, particularly tropical alpine ecosystems, host important biodiversity hotspots in small, primarily remote mountain tops. One of those ecosystems, Afroalpine ecosystems, the habitats above the treeline of tropical African mountains, have experienced long-term spatial isolation and extreme climatic conditions, leading to the formation of "Sky Island" like ecosystems endowed with unique flora and fauna rich in endemics. One of these ecosystems is Ethiopia's Bale Mountains, which is home to Africa's most extensive Afroalpine plateau, Altiplano, with no spacious high summits that provide space for an upward shift. Over the last fifty years, this pristine Afroalpine ecosystem has experienced and suffered from excessive human presence, hence significant LULC change besides climate change. Consequently, the once pristine natural Afroalpine mountain ecosystems have changed entirely cultural landscapes.

Lately, the long-existing environmental relationships that shape Afroalpine mountain ecosystems' stability and instability are changing rapidly in response to the recent rapid global change, especially to the synergistic impacts of drivers of ecosystem change such as Land Use Land Cover (LULC) and climate change. Here, we investigated the effects of fifty years long Spatio-temporal LULC change and climate change on Afromontage and Afroalpine vascular plants richness patterners, particularly that of Afroalpine endemics; effects of current and projected variability of temperature and moisture-related predictor on the diversity and distribution of the phenotypically highly adapted dominant cover types; and possible impacts of the synergy between the main drivers of biodiversity change particularly that of LULC and climate change on the Afroalpine vegetation. The research used *in-situ* plot data, *ex-situ* open data sources, and state-of-the-art research approaches and methodologies.

The fifty-year Spatio-temporal LULC change study identified cover types such as Agricultural Fields, Upper Montane Forest, Afroalpine Grasslands, Afromontane Dwarf Shrubs, and Herbaceous Formations increased overtime. Conversely, Afromontane Grasslands, Closed Erica Forest, Isolated Erica Shrubs, Aroalpine Dwarf Shrubs, and Herbaceous Formations reduced considerably. However, despite some simplification at the lower margins, the Afromontane Rainforest (Harenna Rainforest), located south of the Bale Mountains, has remained relatively stable. Contemporarily, the ecotone between the Upper Montane and the afroalapine ecosystems are "biodiversity loss hotspots." Population growth, infrastructural expansion, frequent fire, over-grazing, deforestation, inadequate conservation and management measures, and lack of protection during the political transition and uncertain political atmosphere are some of the leading local causes of biodiversity loss. Besides, the massive mid to low-altitude areas, formerly sparsely populated agriculturally fertile regions, face large-scale agricultural land acquisition, and land grabbing. LULC change is expected to become even more intensive and is likely to continue imposing unprecedented pressures on the largely endemic biota of the area.

Our finding further indicated hump-shaped species richness patterns across the massif. In addition, the proportion of endemic species increases monotonically towards the summit on all slopes. However, climate change will profoundly impact vascular plants' diversity and richness patterns, i.e., it impacts species' and ecosystems' structure, composition, functioning, and distribution patterns. Furthermore, it will results in a shift in ecosystem boundaries, potentially affecting vulnerable Afroalpine ecosystems and their uniquely adapted species. Our study indicated that future climate change would significantly alter species distribution patterns with a pronounced effect on the Afroalpine ecosystems and endemic species restricted to the Afroalpine plateau, e.g., at 2^{o}C, up to 8.6% of total endemics will become extinct. However, all vascular plants and ecosystems will not respond to the change uniformly.

The ericaceous woody vegetation, located between the low-elevation Broadleaf Forests and high-elevation Afroalpine vegetation, is anticipated to be affected differently. Our model ensemble projections indicated increased dominance and upward range shift of ericaceous vegetation by the first half of the 21st century. It will increase in the western, northwestern, northern, and eastern parts of the massif and the Sanetti plateau. Towards the turn of the 21st century, ericaceous vegetation will continue to increase across its current range and shift towards the Afroalpine meadow while receding from the lower range across the massif. Moreover, the current ericaceous vegetation range correlates to the current temperature and precipitation trends, reaffirming the critical role of temperature and precipitation in determining species distributions along elevation. The competition between Afroalpine specialists and plants with a broader range of distribution will further facilitate the extinction rate of Afroalpine specialists and endemics.

Overall, the dissertation developed innovative research approaches and applied cost-effective and efficient biodiversity monitoring approaches that utilize the vast geospatial data acquired from Remote Sensing and advanced geospatial analysis tools and techniques. In developing countries, environmental management, climate change mitigation, and adaptation decisions are often made without proper consultation with the local stakeholders in a top-down approach that is usually variable with changing government and political transitions. Hence, policy failure and lack of appropriate local conservation and management strategies are the root causes of the Afroalpine biodiversity loss. Therefore, continuous biodiversity monitoring and assessment utilizing state-of-the-art geospatial information and tools and technologies such as Remote Sensing, qGIS, R^2, and others are essential. Recently, information acquired from Remote Sensing provides frequent and consistent data that can be traced a few decades back and cover a large swath of land. Our results indicate the high likelihood of considerable changes in this biodiversity hotspot in Eastern Africa.

Zusammenfassung

Bergökosysteme, insbesondere tropisch-alpine Ökosysteme, beherbergen wichtige Hotspots der biologischen Vielfalt in kleinen, meist abgelegenen Berggipfeln. Die afroalpinen Ökosysteme, welche oberhalb der Baumgrenze in den Bergen des tropischen Afrikas liegen, waren lange Zeit räumlich isoliert und von extremen klimatischen Bedingungen geprägt, was zur Bildung von "Himmelsinseln" führte mit einer einzigartigen Flora und Fauna, die reich an Endemiten ist. Eines dieser Ökosysteme ist das Bale-Gebirge in Äthiopien, in dem sich das ausgedehnteste afroalpine Plateau Afrikas, das Altiplano, befindet, ohne weitläufige Hochgipfel, die Platz für eine Ökosystemverschiebung nach oben bieten würden. In den letzten fünfzig Jahren hat dieses unberührte afroalpine Ökosystem unter der übermäßigen Präsenz des Menschen gelitten, was neben dem Klimawandel auch zu erheblichen Veränderungen der Landnutzung geführt hat. Infolgedessen haben sich die einstmals unberührten natürlichen afroalpinen Bergökosysteme vollständig in Kulturlandschaften verwandelt.

In letzter Zeit verändern sich die seit langem bestehenden Umweltfaktoren, die die Stabilität afroalpiner Bergökosysteme prägen, rasch, als Reaktion auf die jüngsten globalen Veränderungen des Klimas sowie der Landoberfläche und der Landnutzung. In meiner Dissertation untersuchte ich die Auswirkungen eines fünfzigjährigen räumlich-zeitlichen Wandels der Landoberfläche, der Landnutzung und des Klimas auf den Reichtum der afromontanen und afroalpinen Gefäßpflanzen, insbesondere der afroalpinen Endemiten. Ich analysierte die Auswirkungen der aktuellen und projizierten klimabedingten Variabilität des Niederschlags und der feuchtigkeitsbezogenen Vorhersagevariablen auf die Vielfalt und die Verteilung der phänotypisch hochgradig angepassten dominanten Deckungstypen, und die möglichen Auswirkungen der Synergie zwischen Landnutzungs- und Klimawandel auf die afroalpine Vegetation. Dafür wurden In-situ-Daten, offene Ex-situ-Datenquellen und modernste Forschungsansätze und -methoden verwendet.

In der Fünfzig-Jahres-Studie zur räumlich-zeitlichen Veränderung der Landnutzungsformen wurde festgestellt, dass Bewuchsarten wie landwirtschaftliche Felder, Hochgebirgswälder, afroalpines Grasland, afromontane Zwergsträucher und krautige Formationen im Laufe der Zeit zunahmen. Im Gegensatz dazu gingen afromontane Graslandschaften, geschlossene Erica-Wälder, isolierte Erica-Sträucher, afroalpine Zwergsträucher und krautige Formationen erheblich zurück. Dahingegen blieb der afromontane Regenwald (Harenna Regenwald) im Süden des Bale-Gebirges relativ stabil. Die Ökotone zwischen den oberen montanen und den afroalapinen Ökosystemen sind "Hotspots" für den Verlust der biologischen Vielfalt. Bevölkerungswachstum, Ausbau der Infrastruktur, häufige Brände, Überweidung, Entwaldung, unzureichende Schutz- und Bewirtschaftungsmaßnahmen sowie mangelnder Schutz während des politischen Übergangs und der unsicheren politischen Atmosphäre sind einige der wichtigsten lokalen Ursachen für den Verlust der biologischen Vielfalt. Außerdem sind die riesigen mittel- bis niedriggelegenen Gebiete, ehemals dünn besiedelte, landwirtschaftlich fruchtbare Regionen, mit groß angelegtem Landerwerb und Landgrabbing konfrontiert. Es ist zu erwarten, dass die Veränderungen der Landnutzung noch intensiver werden und die größtenteils endemischen Biota des Gebiets weiterhin einem beispiellosen Druck ausgesetzt sein werden.

Ergebnisse meiner Dissertation weisen außerdem auf eine glockenförmige Kurve des Artenreichtums entlang des Höhengradienten hin. Darüber hinaus nimmt der Anteil der endemischen Arten auf allen Hängen monoton zum Gipfel hin zu. Der Klimawandel wird sich tiefgreifend auf die Vielfalt der Gefäßpflanzen auswirken, d. h. er beeinflusst die Struktur, die Zusammensetzung, die Funktionsweise und die Verbreitung von Arten und Ökosystemen. Dies führt zu einer Verschiebung von Ökosystemen, welche gefährdete afroalpine Ökosysteme und ihre besonders angepassten Arten schaden könnte. Ich zeige auf, dass der künftige Klimawandel die Verbreitungsmuster der Arten erheblich verändern wird, mit deutlichen Auswirkungen auf die afroalpinen Ökosysteme und die endemischen Arten, die auf das afroalpine Plateau beschränkt sind. So werden bei einer Temperaturerhöhung von 2 °C bis zu 8,6% aller endemischen Arten aussterben. Allerdings werden nicht alle Gefäßpflanzen und Ökosysteme in gleicher Weise auf die Veränderungen reagieren.

Es wird zudem erwartet, dass die verholzende Erica-Vegetation, die zwischen den Laubwäldern in niedrigen Lagen und der afroalpinen Vegetation in hohen Lagen liegt, unterschiedlich betroffen sein wird. Die Modellprojektionen einer weiteren Studie meiner Dissertation deuten auf eine zunehmende Dominanz und eine Verschiebung des Verbreitungsgebiets der Erica-Vegetation bis zur ersten Hälfte des 21. Jahrhunderts hin. Insbesondere wird sie in den westlichen, nordwestlichen, nördlichen und östlichen Teilen des Massivs und auf dem Sanetti-Plateau zunehmen. Gegen Ende des 21. Jahrhunderts wird die Ercia-Vegetation in ihrem derzeitigen Verbreitungsgebiet weiter zunehmen und sich in Richtung der afroalpinen Wiesen verlagern, während sie sich aus dem unteren Bereich des Massivs zurückzieht. Darüber hinaus korreliert das aktuelle Spektrum der Erica-Vegetation mit den aktuellen Temperatur- und Niederschlagstrends, was die entscheidende Rolle von Temperatur und Niederschlag bei der Bestimmung der Artenverteilung entlang der Höhenlage bestätigt. Die Konkurrenz zwischen afroalpinen Spezialisten und Pflanzen mit einem breiteren Verbreitungsgebiet wird das Aussterben der afroalpinen Spezialisten weiter begünstigen.

Insgesamt wurden im Rahmen meiner Dissertation innovative Forschungsansätze entwickelt und effiziente Ansätze zur Überwachung der biologischen Vielfalt angewandt, die die umfangreichen Geodaten aus der Fernerkundung und fortschrittliche Geodatenanalysetools und -techniken nutzen. In Entwicklungsländern werden Entscheidungen zum Umweltmanagement, zum Klimaschutz und zur Anpassung an den Klimawandel oft ohne angemessene Konsultation der lokalen Interessengruppen im Rahmen eines Top-down-Ansatzes getroffen, der in der Regel mit wechselnden Regierungen und politischen Veränderungen variiert. Politisches Versagen, ein Mangel an lokalen Schutzmaßnahmen und Management–Strategien sind Ursachen für den Verlust afroalpiner Biodiversität. Daher ist eine kontinuierliche Überwachung und Bewertung der biologischen Vielfalt unter Verwendung modernster Geodaten, Werkzeuge und Technologien wie Fernerkundung und geographischen Informationssystemen unerlässlich. Satelliten-Fernerkundung liefert kontinuierlich Daten, die Umweltveränderungen einige Jahrzehnte zurückverfolgen können und eine große Fläche abdecken. Meine Dissertation deutet darauf hin, dass in diesem Hotspot der biologischen Vielfalt in Ostafrika mit großer Wahrscheinlichkeit erhebliche Veränderungen zu erwarten sind.

1. Introduction

1.1 Motivation

Anthropocene's rapid global change (Lewis and Maslin 2015) has further complicated the relationship among different components of the environment, especially that of socioeconomic, political, and ecological systems, more than at any other time since the existence of *Homo sapiens*. The novel environmental phenomena are imposing immense pressure on biodiversity, particularly plants of fragile ecosystems such as Afroalpine mountain ecosystems. In light of the threats posed by recent global change on biodiversity, research insights from biogeography are essential to investigate plants composition, structure, diversity, distribution, and underlaying processes at all hierarchies of ecosystems from a larger scale (landscape) to a smaller scale (plot). Methodologies from biogeography are plausible to study the possible causes of change, stability, and instability in mountain ecosystems across space and time.

Mountains' complex topography, mainly elevation-related spatial isolation driven steep biotic and abiotic gradients, especially Afroalpine mountains ecosystems, support the evolution of unique flora and fauna especially adapted to these unique ecosystems (Hedberg 1951; Troll 1978; Beierkuhnlein 2007; Spehn et al. 2010). Afroalpine ecosystems experience extreme climatic conditions such as low mean temperature, diurnal freeze-thaw cycles (summertime and winter reign every day (Hedberg 1964)) with very low interannual variability, and other energy-related factors such as decreasing total atmospheric pressure, partial pressure of all atmospheric gases (including CO_2), increasing insolation, a higher fraction of UV-B radiation, and ambient humidity (Hedberg 1964; Colwell et al. 2008, Jump et al. 2009). Though these "Sky Islands" (Hedberg 1951) are within a walking distance from their surrounding hot lowlands, they own unique ecological identifying characters that are entirely different and ecologically very far.

Yet, despite their singularity and endowment with abundant uniquely adapted endemics, the Afroalpine ecosystems are the least known of all tropical ecosystems, both as entire or local functioning units (Vuilleumier and Monasterio 1986). With the recent global change, the existing environmental relationships that shape Afroalpine mountain ecosystems' stability and instability are expected to change in response to the synergistic impacts of the different drivers of biodiversity change (e.g., Sala 2000; Olson et al. (2001); MEA 2005). The recent climate and Land Use Land Cover (LULC) change are having a pronounced impact on biodiversity and ecosystems service (Jentsch and Beierkunhlein 2005). Hence, the synergistic impact of drivers of change may trigger range of physiological and morphological biodiversity responses such as persist locally (e.g., in refugia), migrate to more suitable places, change phenotypically (through plasticity or evolutionary adaptation), change abundance, or go extinct (Dawson et al. 2016). Hence, Afroalpine mountains are outstanding sites for testing the relationship between plants and environmental variables (different biotic and abiotic drivers of change), because of their unique position across time and space.

The study area in focus, the Bale Mountain massif, is both locally and globally significant for biodiversity conservation. Therefore, this dissertation aims to provide up-to-date scientific information on the biodiversity of the massif particularly the vascular plants including the challenges they face due to climate and LULC change relaying on Spatiotemporal biodiversity pattern analysis, and altitudinal pattern of richness gradients and climate change relationships. In the area, studies that utilize the existing vast geospatial information and geospatial data analysis tool for biodiversity pattern monitoring and climate change impact assessment are limited or do not exist at all.

Furthermore, over the last fifty years, governments and international organizations have been actively drafting policies and guidelines aiming to safeguard biodiversity. However, most of these policies and guidelines are far from implementation in the developing world and are incomplete as they never address the local issue or are not supported by in-depth local analysis of drivers of change and research on the reach cultural diversity that sustain them to date. Therefore, these mountains are excellent locations to study Climate and LULC change impact on plant diversity and distribution, and diversity pattern studies. The recent advances in geospatial data sources and data analysis tools enable the identification of diversity hotspots, endemism, and rarity, examining the underlying processes that generate patterns in species diversity, identifying areas of conservation importance and priority, and recommending and supporting possible local solutions.

1.2 Thesis Structure

The dissertation addresses the plot to landscape-level spatial and temporal patterns of vascular plant diversity, distribution, and altitudinal patterns of richness gradients in the face of the synergistic impact of climate and LULC change. It examines climate and LULC change as the primary process that generates biodiversity and vegetation patterns change. It starts with a broader introduction chapter that highlights the background, study area, hypothesis, objectives, methods, and major findings. Chapter one assesses the historical LULC change and biodiversity pattern in the Bale mountains area. Chapter two assesses projected climate change impacts on the distributions of one of the dominant cover types, ericaceous vegetation. Chapter three highlights vascular plant species diversity and distribution, altitudinal diversity gradients, and climate change impact on the species distribution, Ethiopian and Bale endemics pattern. And chapter four reviews the synergistic impact of climate and LULC change on Ethiopian mountains.

My goal is to contribute to science, Afroalpine ecosystems and vegetation knowledge basis, biodiversity conservation management, and inspire young scientists. My contribution to each article is clarified. The knowledge gaps, threats, conservation management priorities, and state of current knowledge are discussed. Overall, the dissertation focuses on the synergistic impact of climate and LULC change on vascular plant diversity and distribution patterns along altitudinal richness gradients. A strong emphasis is given to the "Sky Islands," Afroalpine ecosystems biogeography. A large part of the knowledge on vascular plants and local drivers of biodiversity patterns change originates from my own field research.

1.3 Significance of Mountains

Mountain's Ecosystem, Economic and Cultural Significance

Mountains are complex landforms due to the interplay among tectonic and structural elements, climatic processes over geologically short time scales, spatial isolation, and denudational processes (Gerrard 1990; Messerli and Ives 1997; Rahbek et al. 2019b). Besides, the mountain landscapes are characterized by complex topography, soils, and hydrology which results in a high diversity of microclimatic conditions on a small spatial scale (Jump et al. 2009; Körner and Hiltbrunner 2021). Isolation, tectonic history, and complex topography result in elaborate mosaics of unique habitats composed of different adjacently flourished plant species and functional groups (Whittaker 1975; Troll and Lauer 1978; Huston 1994; Beierkuhnlein 2007). Consequently, mountains contribute disproportionately to the terrestrial biodiversity, especially in the tropics, where they host hotspots of an extraordinary ecosystem, species, genetic, and endemics diversity (Grabherr et al. 2000; Körner 2004; Beierkuhnlein 2007; Jump et al. 2012; Steinbauer et al. 2016b; Rahbek et al. 2019a, 2019b).

Mountains are resource-rich biodiversity hotspots that provide many ecosystem services beyond their geographical limits (Messerli and Ives 1997; Körner et al. 2017). With about 25% of all land area, mountain regions are home to more than 85% of the world's species of amphibians, birds, and mammals, many entirely restricted to mountains (Rahbek et al. 2019a). They are home to nearly half of the world's biodiversity hotspots (Myers 2000; Körner 2004; Hoorn et al. 2018) and inhabit about 26% of the global population, and half of humankind depends in one way or the other on mountain resources (Rahbek et al. 2019a). Besides, they are "water towers" that provide approximately 70% of the global freshwater that sustains nearly half of the world's population (Viviroli et al. 2011). In addition, mountains provide timber and nontimber forest products, mineral resources, and many other foods, fiber, and fuel products (Sayre et al. 2018).

Mountains play an array of roles in Earth's biodiversity and affect neighboring lowlands through the biotic interchange, changes in regional climate, and nutrient runoff (Beierkuhnlein 2007; Rahbek et al. 2019a, 2019b). The scenic landscapes, immense biodiversity, and clean air make mountains attractive for recreation and tourism (Singh and Sharma 1998). The cultural values associated with mountain environments range from aesthetic to recreational to spiritual (Sayre et al. 2018). Mountain inhabitants have evolved a high diversity of cultures, including languages and traditional knowledge, due to mountains' solid geographic and ecological barriers to diffusion (Diamond 1999). Furthermore, mountains have spiritual significance and can be sacred places that have long been revered, held in awe, and viewed as symbols of strength, freedom, and eternity (Smethurst 2000). Out of believers' devotion and revered nature mountains harbor secluded spiritual sites surrounded by forests that serve as plant diversity refugia across the globe (e.g., Aerts et al. 2016; Orlowska and Klepeis 2018; Messerli and Ives 1997).

In addition, mountains are strategically essential assets of greater significance in times of peace and conflict. They are the most popular geographic boundaries that play a crucial role in delineating economic, political, and cultural boundaries (AUBP 2013). Mountain ridges, rivers, and cliffs play a vital role in establishing regional, national, and international borders (Brigham 1919).

Mountains modify regional macroclimate regimes and produce many associated microclimate regions (Beierkuhnlein 2007). The steep gradients of temperature and precipitation, and topographic complexity result in many microsites (Messerli and Ives 1997; Beierkuhnlein 2007; Körner 2007), intense physical weathering, various mass movements, the signature of deep-time evolutionary and ecological processes (Rahbek et al. 2019b), an imprint of past and present glaciations, and distinctive associations and patterns of plants (Gil-Romera et al. 2019; Ossendorf et al. 2019). Hence, mountains permit testing ecological theories and questions of adaptive evolution, colonization, diversification, and radiations (Körner 2000; Gehrke and Linder 2009; Hughes and Atchison 2015; Gizaw et al. 2016; Brochmann et al. 2021). In addition, mountain ecosystems are prime for altitudinal pattern analysis, speciation, richness, diversity, and endemism studies (Jump et al. 2012; Steinbauer et al. 2013; Merckx et al. 2015). Mountains are ideal for investigating plant responses to climate change (Kreyling et al. 2010; Chala et al. 2016; Kidane et al. 2019), testing the synergistic impact of climate change and Land use Land Cover Change (LULCC) (Razgour et al. 2020), and comparative island biogeography studies (Sklenar et al. 2014; Steinbauer et al. 2016b; Itescu 2019; Flantua et al. 2020).

Mountains are refugia that serve as corridors of cross-continental migration that allow species to migrate between core habitats and mountain ecosystems (Körner 2003; Rahbek et al. 2019b). Served as refugia for organisms during past climatic changes, they are anticipated to provide protection for flora and fauna under forthcoming climatic change (Körner 2003; Jump et al. 2009; Scherrer and Körner 2011). However, some mountains that were glaciated and uninhabitable during the Pleistocene are hosting novel species compositions, attributing to their geodiversity, topography, latitudinal and longitudinal location (personal com. Beierkuhnlein 2021).

Mountains are hypothesized to be sensitive to perturbation (anthropogenic or natural) and climate change (Körner 2003; Nagy and Grabherr 2009; Grabherr et al. 2000; Spehn 2011; Winkler et al. 2016), potentially showing signs of change before other terrestrial ecosystems (Gerrard 1990; Grabherr et al. 2000; Messerli and Ives 1997). Especially tropical mountain ecosystems, which are ecologically extremely far yet physically at a walking distance to their surrounding tropical hot lowlands are highly significant for climate change impact studies. Hence, the central theme of this thesis is investigating the imminent threat posed by the synergy of climate and LULC change on the Afroalpine mountains from plot to the landscape.

Mountain Research Development

Mountains' scenic attraction, complex geomorphology, and spectacular altitudinal zonation have inspired generations of scientists. The short thermal zonation associated with flora zonation makes mountains ideal 'natural laboratories' and favored locations for studying climate change impacts (Körner et al. 2003; Körner et al. 2011; Razgour et al. 2020). The early work on mountains stems from geologists and others developing theories about mountain formation (Messerli and Ives 1997). Yet, mountains have been an essential experimental site for developing contemporary ecological theories. Often three names come to one's mind when talking about the fundamentals of mountain studies: Horace Benedict de Saussure, who climbed and studied the Mont Blanc in 1787; Alexander von Humboldt who investigated the environment during his attempt to ascend the Chimborazo in 1802; and Carl Troll, who founded the International Geographical Union's Commission on High-altitude Geoecology in 1968 (Messerli et al. 2011). Modern mountain research generally traces back to Alexander von Humboldt and his expedition to tropical mountains in the Americas in the early 1800s (Stadelbauer 2008; Jackson 2009).

The idea that variations in climate exert a strong influence on plant distribution dates back in the literature to around the 5th century BC (Woodward 1987). However, Humboldt's approach was novel because he used measuring instruments and integrated human land use when characterizing elevational zones (Rahbek et al. 2019a). Humboldt coined the central paradigm of his scientific legacy: Everything is connected; removing one factor or item will inevitably affect others (Körner and Spehn 2019). He was the first to discuss quantitative differences in the floras of various regions on earth regarding total species numbers and the relative importance of different families (Mutke and Barthlott 2005). He further explained that altitudinal zonation results from complex gradients of several environmental factors, primarily temperature (Messerli and Ives 1997). Humboldt's Essay "*Ideen zu einer Geographie der Pflanzen*" is still relevant to science and society (Jackson 2009).

Inspired by the works of Alexander von Humboldt, centuries of mountain studies have revealed many of the general principles and processes that constitute biogeography, ecology, botany, and evolutionary biology (Jackson 2009; Rahbek et al. 2019a; 2019b). Ives (1985), Allan (1992), Messerli and Ives (1997), Messerli (2011), and Gonzalez-Trueba and Garcia-Ruiz (2012) gave overviews on the upsurge and genesis of mountain research during the 20th century. Furthermore, the 20th century has witnessed intensifying tropical mountain research and its expansion towards the remote parts of the world, such as Afroalpine ecosystems. Among many others, the remarkable works of Carl Troll, the pioneer of the terms 'Landscape Ecology' (Landschaftsökologie) and 'Geoecology,' specifically mountain geoecology, and the contribution of Olov Hedberg (who was inspired by Carl Troll) to the research on Afroalpine ecosystems are worth remembering.

Despite substantial scientific community attention and ample scientific evidence on the threats to mountain ecosystems, policy and politics fail to acknowledge mountains' significance in the 1972 Stockholm conference on the world's environment. The conference did not mention mountains among its 109 formal recommendations (Allan 1992; Grabherr et al. 2000). However, in the mid-1970s, research neglect of mountains, especially those in developing countries of the global south, was brought to attention (Eckholm 1975). Since then, global change and human impact on the environment have led to an upsurge in scientific, policy, and political initiatives worldwide (Gerrard 1990; Messerli et al. 2011). Ives (1985), Gerrard (1990), and Messerli and Ives (1997) argue the growing interest was stimulated by the UNESCO Man and the Biosphere Program (1971): Impact of Human activities on Mountains Environment.

In the 1980s, mountain research began expanding from ecological science to social sciences. Then onwards, the understanding that mountains are unique from a socioeconomic, cultural, and political perspective has gained traction (Messerli et al. 1990; Smethurst 2000). The subject of technical articles taking a global perspective of the problems and challenges that mountains face because of Global Change processes has started during this time. Influential journals such as Mountain Research and Development, Arctic, Antarctic, and Alpine Research, Pirineos, Revue de Géographie Alpine, and Journal of Mountain Science started during this period (Gonzalez-Trueba and Garcia-Ruiz 2012).

The early 1990s brought a turning point, especially when the United Nations Convention on Environment and Development (UNCED) in Rio de Janeiro in 1992 explicitly adopted mountains in its agenda of sustainable development (Grabherr et al. 2000; Gonzalez-Trueba and Garcia-Ruiz 2012). Mountain conservation became a recognized policy priority globally since its inclusion in Chapter 13 (Managing Fragile Ecosystems: Sustainable Mountain Development) of Agenda 21 at this Conference (Ives et al. 1997). Besides, during the 1990s, mountain research evolved to include climate and LULC change, and ecosystem services (mineral ores, water, nomadic pastoralism, and scenic values) (Stadelbauer 2008). Besides, many long-term global observation networks were established in the '90s, mainly for the comparative study of climate change impacts on mountain biodiversity, specifically plants response to climate change. The UN announcement of 2002 as the international year of mountains further climaxed the attention on mountains (Stadelbauer 2008; Gonzalez-Trueba and Garcia-Ruiz 2012).

Grabherr et al. (2000) and Messerli et al. (2011) summarized the genesis of the global alpine observation networks. One of the long-standing research networks is the Global Observation Research Initiative in Alpine Environments (GLORIA). It was founded in 2001. To date, the program has a total of 115 GLORIA target regions worldwide distributed from the poles to the tropics (GLORIA 2021). Other recent global programs devoted explicitly to mountains are the Global Mountain Biodiversity Assessment (GMBA) and the Mountain Research Initiative (MRI) (Messerli et al. 2011). GMBA and MDI are international and cross-disciplinary collaboration platforms for the assessment, conservation, and sustainable use of mountain biodiversity (Körner and Spehn 2019; GMBA 2021, MDI 2021).

The developments of international platforms established to recognize the significance of global mountains are summarized in Messerli et al. (2011). Their assessment identified the scientific and political initiatives at the global level since the beginning in the 1970s discussed the outcomes of the 2010 Perth conference and Rio de Janeiro 2012 and beyond.

Mountain Definition

The significance of mountain research is hidden in the problems of definition (Funnell and Price 2003). Answers to the questions ''what is a mountain?'' and ''where are the mountains of the world?'' are complex (Sayre et al. 2018). Therefore, establishing an all-inclusive pertinent definition of mountains is crucial for monitoring and conserving mountain biodiversity, and it supports highlighting mountains' importance in global biodiversity inventories (Körner et al. 2017), as called for in Sustainable Development Goals 6 and 15 of the United Nations 2030 Agenda for Sustainable Development (Sayre et al. 2018). Besides, the exact definition and quantification offer precision and a robust framework for studying mountain biodiversity at all ecosystem levels. To date many have studied mountains and attempt to formulated definition that establish some qualifying criteria and provide global inventory (see Funnell and Price 2003; Körner et al. 2017).

Until recently, even though mountain definition has remained an active challenge for research, there are no unifying definitions and classifications beyond a simple definition that relies on a combination of 'steepness of slope' and 'altitude' (Gerrard 1990; Messerli and Ives 1997). Messerli et al. (1990) and Smethurst (2000) suggest mountain definition should be more inclusive i.e., a definition that characterized mountains by relief which results in altitudinal, ecological, climatic, and land use differentiation that produces geomorphic processes or mountain hazards that leads to clear highland-lowland gradients and mobility, and a definition that includes interactions in natural and social systems, humid-arid systems, and anthropogenic impacts such as climate and LULC change.

Recently, there have been few attempts to map the mountains of the earth consistently and rigorously. Troll (1973), Gerrard (1990), Kapos et al. (2000), Meybeck et al. (2001), Funnell and Price (2003), Körner et al. (2011, 2017), Sayre et al. (2014), Karagulle et al. (2017), and Hoorn et al. (2018) have worked on establishing a definition for mountains areas. None of these approaches was generally accepted. Current definitions that are based on the analysis of vast geospatial information and existing geospatial analysis tools are World Conservation Monitoring Center (WCMC) developed by Kapos et al. (2000), which takes ruggedness; the Global Mountain Biodiversity Assessment (GMBA) developed by Körner et al. (2011), that considers only ruggedness to measure the vertical amplitude within a predefined space; and Karagulle et al. (2017) that take into consideration slope inclination, an index of variation in vertical relief, and an index of the profile character.

Kapos et al. (2000) and Körner et al. (2011) define whether a specific grid area of the earth's surface is mountainous or not. Still, they don't define mountain territory as a geographical region (Körner et al. 2017), while Karagulle et al. (2017) identified global ecological land units. The differences in conceptual definition, methodology, and spatial resolution of source data can differ in the extent and location of lands classed as mountains (Sayre et al. 2018). Sayre et al. (2018) summarized and compared Kapos et al. (2000), Körner et al. (2011) and Karagulle et al. (2017) definition, which are the most recent ones (**Table 1**). Others such as Rahbek et al. (2019c) argued that mapping montane regions should be based on crucial topographic features including elevation, aspect, and slope.

Table 1: General comparison and characterization of the Kapos et al. (2000), Körner et al. (2011), and Karagulle et al. (2017) definitions of the global mountain area. (Adopted from Sayre et al. 2018)

Source	Kapos et al. 2000	Korner et al. 2011	Karagulle et al. 2017
Purpose	to delineate global mountain forests	to develop a standardized definition, mountain biodiversity map, and subdivision of life zones along elevation gradients.	global landforms layer with several different types of plains, hills, and mountain features.
Geospatial data format	Raster	Raster and vector polygon	Raster
Year source DEM was produced	1996	2005	2010
Approximate spatial resolution of source DEM at the equator	1000 m	1000 m	250 m
Global pixel resolution for attribution as mountain terrain	1000 x 1000 m	4600 x 4600 m	250 x 250 m
Classifier(s)	Elevation, Slope Relative relief	Relative relief	Slope class, Relative relief Profile
Number and types of mountain classes	six classes: ✓ > 4500 m ✓ 3500–4499 m ✓ 2500–3499 m ✓ 1500–2499 m ✓ 1000–1499 m ✓ 300–999 m	one class: mountain terrain	Four classes: ✓ High mountains ✓ Scattered high mountains ✓ Low mountains ✓ Scattered low mountains
Distinguishing features	✓ Original, mature, DEM-derived resource ✓ Includes forest attributes	✓ Conceptually simple ✓ Includes name attribution and considerable value-added attribution related to climate and biodiversity	✓ High spatial resolution ✓ Complex characterization of terrain features including profile (gently sloping areas in upland regions)
Percent of global mountain area	24.3%	12.3%	30.5%
Estimated global population	~ 900 million	~ 400 million	~ 1050 million

Körner et al. (2017), in their comparison of the WCMC and GMBA definitions, identified that the WCMC approach arrives at twice the global mountain area and much higher human population numbers than the approach of GMBA. This is explained by the inclusion of (mostly) low latitude hill country below 600m elevation. However, Rahbek et al. (2019c) reviewed the mountain definition based on the definitions of Kapos et al.'s (2000) and Körner et al.'s (2011, 2017). Hence, their map presents a global inventory of the mountain regions of the world encompassing 136 unique polygons and covering approximately 25% of the emerged lands of the planet (32.9 million km^2), which is closer to Kapos et al. (2000) calculation which is 24.3%. Therefore, a clear mountain definition that relies on standardized criteria is vital to quantify mountain ecosystems from a national to a global scale. Such methodologically and scientifically sound mountain definitions lack for developing countries like Ethiopia. Hence, the existing mountain definition for Ethiopian highlands and the rest of the Afroalpine landscape in Africa need to be revisited.

1.4 Tropical Mountains

Tropical mountain ecosystems contribute disproportionately to the terrestrial biodiversity of the Earth (Diaz et al. 2006; Richter 2008; Rahbek et al. 2019a). The world's main biodiversity hotspots of extraordinary richness and diversity with a high proportion of restricted-range endemics are in tropical mountains (Myers et al. 2000; Nagy and Grabherr 2009). Yet, biodiversity varies markedly among tropical mountain regions (Antonelli et al. 2018; Rahbek et al. 2019a, 2019b). Regions of high geodiversity (Gerrard 1990; Barthlott et al. 1996; Breckle 2002), especially in mountain areas of the humid tropics and subtropics, harbor the highest species numbers (Mutke and Barthlott 2005). For example, the Northern Andes capture roughly half of the world's climate types in a small region, much more than is covered in nearby Amazon, a region more than 12 times larger (Rahbek et al. 2019a).

On the top of the high tropical mountains are tropical alpine ecosystems. These are ecosystems within the tropics above the natural elevation limit of a contiguous, closed-canopy forest where trees do not persist yet uniquely adapted flora, and fauna diversity thrives owing to the selection of traits and evolutionary adaptation (Hedberg 1951; Smith and Young 1987). Such ecosystems occur in Central America, South America, Africa, New Guinea, Irian Jaya, Borneo, Java, Sumatra, La Réunion, and Hawaii. They are regionally known as "paramo" mesic areas of the northern Andes, "puna" drier areas of the central Andes, "jalca" mesic areas in the transitional zone between the paramoto the north and the puna to the south, "zacatal" on the Mexican volcanoes, and "Afroalpine" in Africa (Monasterio and Vuilleumier 1986; Smith and Alan 1987; Rundel 1994).

The resemblance of tropical alpine ecosystems, "alpine-like," to that of polar latitudes, has been the predominant opinion for a long time (Grabherr et al. 2000; Nagy and Grabherr 2009). However, these ecosystems are located above the hot and wet lowlands, extending into climatic conditions superficially like those Arctic, which are substantially different nevertheless (Troll 1943; Flantua et al. 2020). The asymmetry of the northern and southern hemisphere in a longitudinal and latitudinal profile, the global landmass induced oscillations of the main climatic variables i.e., temperature and precipitation difference at high altitude, the intensity of solar radiation, the position of the tropical belt, and circulation of air masses at low latitude are some contributing factors for the difference (Hedberg 1951, 1964; Troll 1973).

Tropical alpine areas experience a year-round growing season, with significant changes occurring in the daytime to nighttime temperature and energy budgets (Sarmiento 1986; Rundel 1994). In tropical mountains, rainfall varies much more than temperature since it heavily depends on the geographic conditions of individual mountain systems (Sarmiento 1986).

Unlike the wet season, the dry season has relatively higher daytime maximum temperatures and lower nighttime minimum temperatures at the tropical alpine zone (Hedberg 1964). In the alpine zone, diurnal freeze-thaw cycles are typical (Hedberg 1951; Hillman 1988). This "summer every day, winter every night" pattern is characteristic of tropical alpine areas (Hedberg 1951). The variation in temperature and intense insolation favored distinctive morphological, physiological, and life-history characters (Smith and Alan 1987; Rundel 1994). Hence, a direct comparison of high tropical mountains with high latitude zones is not feasible (Monasterio and Vuilleumier 1986; Stadelbauer 2008). Tropical alpine ecosystems are much more diverse, rich in endemics, and floristically more complex than temperate and arctic systems (Testolin et al. 2021).

1.5 Afroalpine Ecosystems

Afroalpine ecosystems, tropical mountain ecosystems in Africa, occur in isolated patches restricted to peaks of the high mountains of the East African Rift System (EARS) and Cameron-Nigeria Mountain ranges between the Tropic of Capricorn and Tropic of Cancer (Hedberg 1964; Gehrke and Linder 2014)**.** EARS is the most prominent rift system on Earth that transects the high-elevation East African Plateau, famous for its tectonics and geology, and has also been suggested to be the 'cradle of mankind' (Ring 2014). The solitary peaks of the Afroalpine along the EARS rise from a plateau 1000 - 2000m asl high (Hedberg 1951). Across African Mountains, areas on average higher than 3200m asl are the Afroalpine and Subalpine ecosystems (Hedberg 1964; Smith and Alan 1987). The lower elevational limits of the Afroalpine belt of Afroalpine mountains vary between 3400 and 3800m asl except for Kilimanjaro, where it is 4000 m asl (Hedberg 1964), and the upper limit of plant life is often at 4600 to 5000m asl e.g., the grass *Poa ruwenzorensis* at about 5000m on the Ruwenzor (Nagy and Grabherr 2009).

The Afroalpine regions are home to globally significant biodiversity hotspots and endemic bird areas (Mittermeier et al. 2004). Afroalpine plant communities are typically composed of a mixture of low-growing, perennial life forms (e.g., low-stature woody shrubs, herbaceous forbs, graminoids, cushions), with the relative abundance of each related to local geomorphological and climatic factors. Giant rosettes, tussock grasses, acaulescent rosettes, cushions, and sclerophyllous shrubs are some of the dominant Afroalpine belt phanerogamic life forms (Hedberg 1964; Brochmann et al. 2021). In Africa, alpine ecosystems are scattered in four major mountain regions: the Ethiopian Highlands, The Eastern Arc Mountains, The Albertine Rift, and Cameroon-Nigeria Mountains **(Fig.1).**

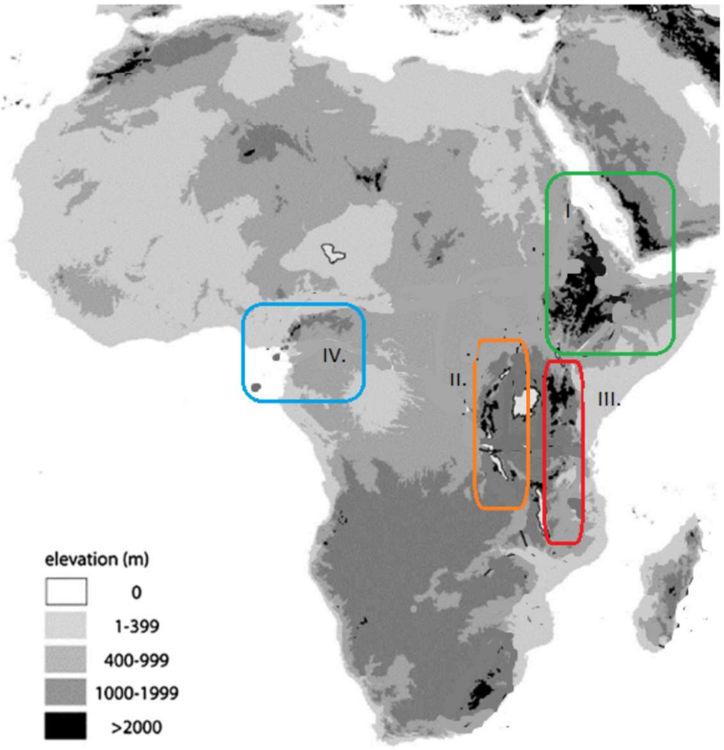


Fig. 1: Distribution of Afroalpine regions in Africa according to White (1983) adapted from Gehrke and Linder (2014). Elevation in meters is indicated by grey scale. I. Ethiopian Highlands, II. The Albertine Rift (Kivu-Rwenzori), III. The Eastern Arc Mountains (Imatong-Usambara), and IV. Cameron-Nigeria Mountains (West Africa).

The Ethiopian Highlands

The Ethiopian highlands are rugged mountain masses along the northern part of the East Africa rift valley systems (EARS) in Ethiopia, Eritrea, Somalia, and Yemen. The contiguous and elevated Ethiopian Plateau is divided by the Great Rift Valley into one northwestern (NWE) and one southeastern (SEE) region, both characterized by high peaks and mountain ranges (Chala et al. 2016). These mountains result from an older topographic uplift, which occurred ~24Ma yr ago (Ring 2014). They comprise the largest continuous area of high elevation in Africa, with much of its area higher than 1500m asl. The highest summit is Ras Dashen 4626m asl (Simien Mountains). Other prominent mountains are the Bale Mountains (4385m asl), the Choke Mountains (4100m), and the Gughe Mountains (4200m asl).

The Albertine Rift

Mountains within this range cover a mixture of ancient crystalline mountains and young volcanoes along the western margins and parts of the eastern margins of the Great Rift Valley (Burgess et al. 2007). These mountains are located along the Zaire-Uganda-Rwanda border. Topographic uplift occurred ~10Ma (Ring et al. 2014, 2018). Some of the prominent mountains are Rwenzori (5,119m asl), and Virunga (4507m asl). Further to the south, other isolated mountain blocks include Mt. Bururi (Burundi), Mt. Kabobo, and the Marungu (Democratic Republic of Congo). All these mountains but Ruwenzori are of volcanic origin (Hedberg 1964). Most of the massifs rise to between 2,000m to 3,500m asl, with several summits rising above 3000m asl (Hedberg 1964; Sarmiento 1986).

The Eastern Arc Mountains

The Eastern Arc Mountains are in Kenya and Tanzania and are under the direct climatic influence of the Indian Ocean. Though physically separated, these mountain ranges share similar geomorphology and ecology (Hedberg 1964). These mountains result from topographic uplift that occurred ~12Ma, magmatically highly active with large shield volcanoes and characterized by high elevation (Ring et al. 2018). The area is an important center of endemism in Africa for plants and vertebrates (Burgess et al. 2007). Prominent mountains are Mt. Kilimanjaro (5899m asl) and Mt. Kenya (5195m asl).

Cameron-Nigeria Mountains

These isolated mountain ranges cover a chain of volcanoes in West Africa of increasing age from the coast towards the interior and along the border between Nigeria and Cameroon (Burgess et al. 2007). Mt. Cameroon (4070 m asl) is a single massive structure of predominantly Tertiary origin but has been active ever since with more than ten major events in the 20th century (Bussmann 2006). It is one of the wet mountains in the tropics. The upper belts of these mountains are exceptionally wet, with more than 8000mm of precipitation at 1000m asl declining to approximately 2000mm at the highest peak (Sarmiento 1986).

1.6 Ethiopian Afromontane Ecosystems

The Ethiopian highland plateau is the approximate equivalent of the Andean altiplano, whereas the Afroalpine ecosystems, are comparable to the Andean paramo (Monasterio 1986). These mountains are geographically isolated and orographically complex “Island like ecosystems” located within the tropical to subtropical matrices with differing climates and high land-use pressure. Ethiopia is known for the largest montane areas in tropical and subtropical Africa, which are at the center of East Africa's diversity hotspot (Mutke et al. 2001; Mittermeier et al. 2004). Significantly, the Afroalpine ecosystems on isolated mountains harbor many endemic flora and fauna (Hedberg 1951; Hillman 1988; Miehe and Miehe 1994; Friis et al. 2005). Woldemariam (1990) defined Ethiopian mountain areas as areas above 1500m asl, constituting up to 43% of Ethiopia's landmass. It has been widely adopted in Ethiopia (e.g., Getahun 1984; Gamachu 1990; Grosjean and Messerli 1990; Miehe and Miehe 1994). However, this definition needs revision considering the recent global definitions (see Kapos et al. (2000), Körner et al. (2011), Sayre et al. (2018), and Rahbek et al. (2019c)).

Like mountains on top of mountains, the Ethiopian plateau 'roof of Africa' rises above the plateau that lies at 2500m asl and comprises 80% of the landmass of Africa above 3000m asl (Monastrio and Vuilleumier 1986). Several isolated mountain summits surpass 3000m asl to culminate in the frosty Afroalpine zone. These Afroalpine areas that emerge above the plateaus are geographic islands of diversity and home to the largest Afroalpine habitat in Africa (Laurenson et al. 1998; Mutke et al. 2001). At the Afroalpine zone climate near 0°C persists all year round, sometimes even with a snow cover lasting a couple of days in mountains like Ras Dashen (Hurni and Ludi 2000). Until recently, these mountains were studied as relatively isolated units (Messerli and Hurni 1990). However, they are included in the exchange systems integrating multiscale biogeographic dimensions (Messerli et al. 1990).

In terms of biodiversity conservation and other ecosystem services, the significance and influence of these mountains exceed their spatial limits reaching further beyond surrounding lowlands (Kidane et al. 2012). They have been centers of ancient human residence, sources of livelihood, and socioeconomic activities due to their agricultural productivity, favorable climate, safety, and rich natural resources (Getahun 1984; Gebreegziabher 1988; Grepperud 1996; Darbyshire et al. 2003). Besides, these mountains are home to indigenous people, who have immense traditional knowledge and cultural diversity (Kidane et al. 2012). Biodiversity loss in the Ethiopian mountains will thus immediately and directly impact the livelihood of many people and will have far-reaching implications.

Many Ethiopian high mountain ecosystems have been inaccessible and remote due to their high elevation and rough terrain. The mountain's ecosystems have been free from excessive direct and indirect anthropogenic disturbances until the mid-1980s and sparsely inhabited until the early 1960s (Stephens et al. 2001). Recently, these mountains are falling under faster than usual synergistic impacts of climate and LULC change. One of these mountains is the Bale Mountains, home to one of Africa's prominent and pristine Afroalpine ecosystem (Kidane et al. 2012).

2. Vascular Plant Species Diversity and Richness Patterns, and Endemism

The global plants' diversity, distribution, and richness patterns vary across time and space. It changes in three-dimensional space; latitudinal (polar wards), altitudinal (towards mountain summit), and energy and moisture gradients (Woodward 1987; Beierkuhnlein 2007; Körner 2007; Nagy and Grabherr 2009). Temperature and moisture are important in limiting the distribution of plant species. Along mountains, a 1°C increase in mean annual temperature results in a range change of ~167m in altitude but ~145km^{-1} in latitude (based on a temperature lapse rate of -6ºC km^{-1} altitude and -6.9ºC 1000 km latitude) (Monastrio 1986; Körner 2003; Colwell et al. 2008). The latitudinal bands are often broad and poorly defined (Mutke and Barthlott 2005; Jump et al. 2009). In contrast, limited water availability and high temperatures result in a direct climatic limitation on plant species expansion towards the opposite or equatorial direction in many regions (Woodward 1987; Colwell et al. 2008). Besides, the diversity patterns of vascular plants correlate with different geodiversity measures (Gerrard 1990). Hence global centers of vascular plant diversity coincide with highly geodiverse areas in the tropics and subtropics (Barthlott et al. 1996).

Plant species richness patterns are focal points of biogeography and has attracted interest since the early nineteenth century. Naturalists like Von Humboldt and Wallace set out to discover remote parts of the world to seek answer to an important question, "why some places contain more species than others?" (Barthlott et al. 2007). However, the most comprehensive global patterns of plant species richness have been known at least since the work of Wulff (1935). Still, the quest for a unified theory for global diversity patterns continues (Rahbek et al. 2019a). Over the last two decades, advances have been made to understand the large-scale biogeographic gradients of richness and endemism from global to continental, mainly due to the availability of plant species distribution data, advances in geospatial information, and methodological advances in geospatial analysis tools. Barthlott et al. (1996), Mutke and Barthlott (2005), Barthlott (2005, 2007), Antonelli et al. (2018), and Rahbek et al. (2019a, 2019b) analyzed global patterns of plants richness and diversity. Myers et al. (2000) and Mittermeier et al. (2004) identified global biodiversity hotspots and set conservation priorities.

Wulff (1935), in his analysis of global vascular plant diversity and richness, indicated the humid tropics of South-East Asia and the Neotropics as centers of global maxima of plant species diversity. Some of the most recent studies (e.g., Gerrard (1990), Barthlott et al. (1996), Olson et al. (2001), Breckle (2002), Mutke and Barthlott (2005), Barthlott (2005, 2007), and Rahbek et al. (2019a, 2019b) refined Wulff's work and indicated the global centers of vascular plant diversity coincide with highly structured, geodiverse areas in the tropics and subtropics. These are the Chocó-Costa Rica region, the tropical eastern Andes and the northwestern Amazonia, the east Brazil, the northern Borneo, New Guinea, East Africa mountains, South African Cape region, southern Mexico, and East Himalaya, western Sumatra, Malaysia, and eastern Madagascar.

In general, regions of high geodiversity especially in mountain areas of the humid tropics and subtropics, harbor the highest species numbers (Gerrard 1990; Barthlott et al. 1996, 2005, 2007). A comparison of species richness of biomes as delineated (Olson et al. 2001), shows that tropical broadleaf forest reaches species numbers up to 10,000 species per 10,000km^2, e.g., in the mountain ranges of Costa Rica (Davis et al. 1997) or up to 5,000 species on 1,200km^2 at the Mt. Kinabalu, Borneo (Barthlott et al. 2005). These absolute maxima are closely linked to mountainous areas (Barthlott et al.2005).

Other regions such as tropical and subtropical coniferous forests and Mediterranean climate areas are also very species rich (Barthlott et al. 1996). In contrast, Tundra and Taiga regions harbor the lowest mean species richness. Absolute minima can be found in hyperarid areas of the Sahara and Atacama Desert and in Arctic and Antarctic environments (Barthlott et al. 1996, 2005, 2007). The taxonomic richness of vascular plants does not show uniform richness patterns across the globe. For example, gymnosperms diversity is the same in the main diversity centers of southeast Asia as for all other vascular plants. Yet, there is low gymnosperm diversity in other parts of the tropics and subtropics (e.g., Tropical Africa) (Mutke and Barthlott 2005).

The striking altitudinal patterns of diversity and richness gradients in mountain regions are typically restricted to the relatively narrow and well-delineated altitudinal thermal bands (Körner 2007; Beierkuhnlein 2007; Körner et al. 2011). Each elevation zone supports specific communities of plants and animals adapted explicitly to that zone and human activities (Beierkuhnlein 2007). Yet, the relation between elevation and biodiversity/species richness patterns and the underlying causes is poorly understood or immature (Rahbek 2005).

Generally, species richness tends to decrease with altitude (Grytnes 2003a, 2003b; Steinbauer et al. 2016a), while endemic species richness increases (Steinbauer et al. 2016a; Kidane et al. 2019). Several studies have documented a nonmonotonic pattern of species richness (Grytnes 2003a; Bhattarai and Vetaas, 2003; Rahbek 2005; Steinbauer et al. 2016a). However, the most observed pattern of diversity along altitude is a midaltitude bulge or hump-shaped distribution pattern (Lomolino 2001; Grytnes 2003a; Rahbek 2005; Steinbauer et al. 2016a Steinbauer et al. 2018; Kidane et al. 2019). At the midaltitude, there are intense species-species interactions, high disturbances, and relatively larger areas (Losos and Schluter 2000). The midaltitude elevations of tropical mountains are species-rich systems with a higher speciation rate (Grytnes 2003a; Bhattarai and Vetaas, 2003; Rahbek 2005; Steinbauer et al. 2016a). Besides, in the tropical mountains, the midlatitudes receive maximum rainfall. Moreover, it is an area where most lowland species leading edge and most alpine species trailing edge meets, fire and other anthropogenic disturbances are higher (Kidane et al. 2019).

Climate change is predicted to alter the geographic distribution of plant species at global to local scales (Jump et al. 2009). Especially in Afroalpine ecosystems, the synergy between climate change and local

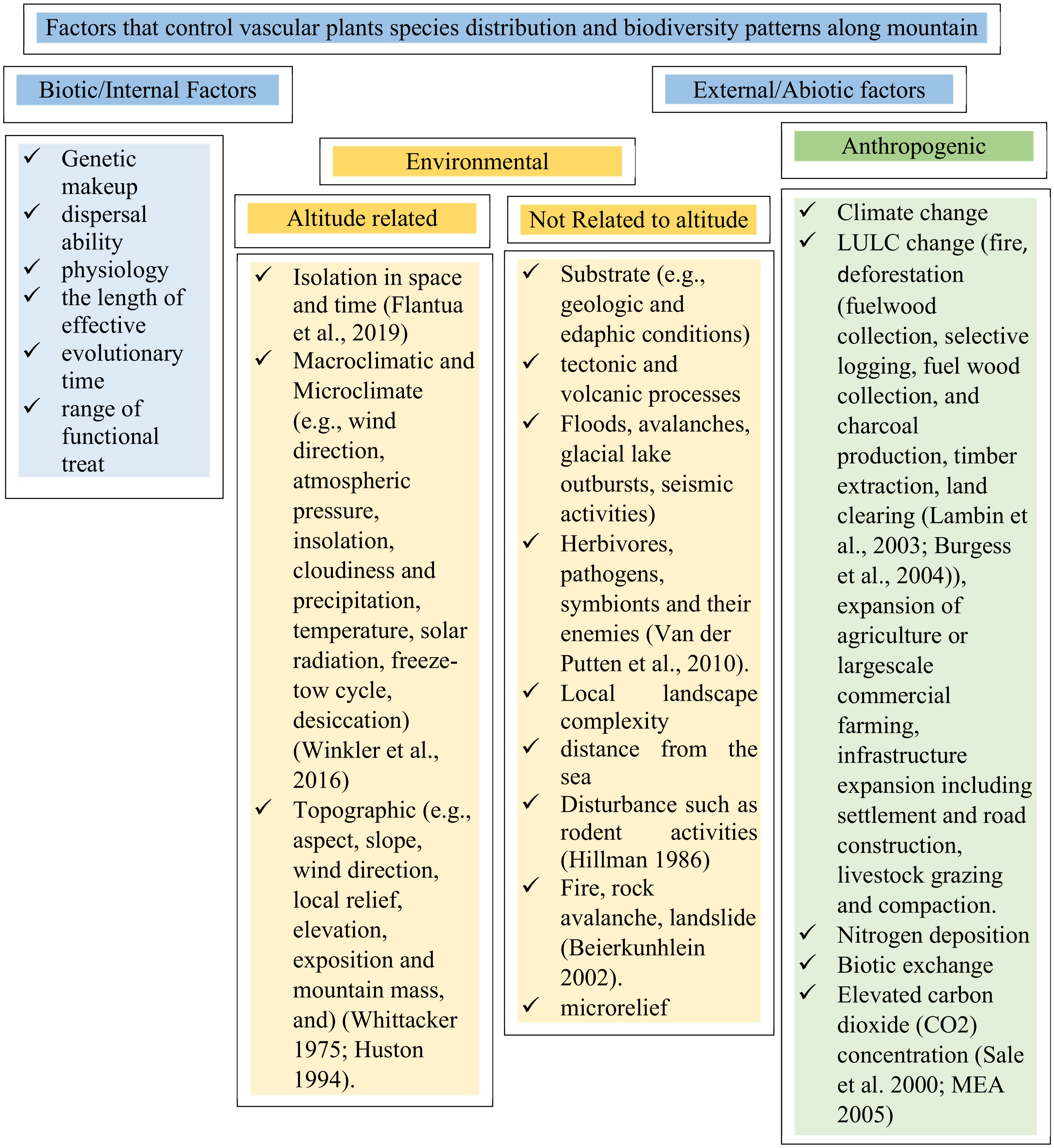
LULCC is expected to shape biodiversity richness and distribution patterns rapidly. Understanding the relationships and analyzing their underlying mechanisms is important (Jentsch and Beierkuhnlein 2003). The Bale Mountains are one of the natural experiment sites where one can study the impact of the synergy and carry out studies that focus on the understanding of the poorly understood empirical basses of these altitudinal biodiversity patterns.

3. Factors Controlling Altitudinal Zonation

The extreme species richness of tropical mountains cannot be explained under traditional climatic hypotheses only (Flantua et al. 2020). Mountains generate and maintain high biodiversity and endemism because of the high variability due thermal gradients, complex topography, and resource-related features that provide different niches (Whittaker 1975; Sarmiento 1986; Körner 2003; Beierkuhnlein 2002b; Richter 2008; Nagy and Grabherr 2009; Flantua et al. 2020). Mutke and Barthlott (2005), Colwell et al. (2008), and Jump et al. (2009) identified decreasing total atmospheric pressure, partial pressure of all atmospheric gases (including CO_2), increasing insolation, higher fraction of UV-B radiation, steep gradients in temperature, and ambient humidity occurring over distances of meters are the main climatic and physical factors relevant to complex altitudinal patterns.

Mountains' complex topography and geomorphology resulted in unique habitats such as the insular-like ecosystems on tropical mountain tops (Itescu 2018; Steinbauer et al. 2016a). This relative insularity has contributed to high species richness and endemism (Monasterio and Vuilleumier 1986; Buytaert et al. 2011; Merckx et al. 2015). Besides, similar to true islands and island-like systems, endemic richness can be further explained by age, reduction of land area, and elevation (Steinbauer et al. 2016a).

In general, there are two categories of altitude-related environmental changes factors: those factors that are physically tied to meters above sea level (m asl) (e.g., atmospheric pressure, temperature, moisture, and clear-sky turbidity), and factors that are not generally altitude specific (e.g., hours of sunshine, wind, geology, fire, and even human land use) (Körner 2007). The marked biogeographical boundary and the reorganization of species' geographical ranges are the results of different biotic and abiotic (Whittacker 1975; Van der Putten et al. 2010) and internal and external factors (Huston 1994) (Fig. 2).



Factors that control vascular plants species distribution and biodiversity patterns along mountain

Biotic/Internal Factors

- ✓ Genetic makeup
- ✓ dispersal ability
- ✓ physiology
- ✓ the length of effective
- ✓ evolutionary time
- ✓ range of functional treat

External/Abiotic factors

Environmental

Altitude related

- ✓ Isolation in space and time (Flantua et al., 2019)
- ✓ Macroclimatic and Microclimate (e.g., wind direction, atmospheric pressure, insolation, cloudiness and precipitation, temperature, solar radiation, freeze-tow cycle, desiccation) (Winkler et al., 2016)
- ✓ Topographic (e.g., aspect, slope, wind direction, local relief, elevation, exposition and mountain mass, and) (Whittacker 1975; Huston 1994).

Not Related to altitude

- ✓ Substrate (e.g., geologic and edaphic conditions)
- ✓ tectonic and volcanic processes
- ✓ Floods, avalanches, glacial lake outbursts, seismic activities)
- ✓ Herbivores, pathogens, symbionts and their enemies (Van der Putten et al., 2010).
- ✓ Local landscape complexity
- ✓ distance from the sea
- ✓ Disturbance such as rodent activities (Hillman 1986)
- ✓ Fire, rock avalanche, landslide (Beierkunhlein 2002).
- ✓ microrelief

Anthropogenic

- ✓ Climate change
- ✓ LULC change (fire, deforestation (fuelwood collection, selective logging, fuel wood collection, and charcoal production, timber extraction, land clearing (Lambin et al., 2003; Burgess et al., 2004)), expansion of agriculture or largescale commercial farming, infrastructure expansion including settlement and road construction, livestock grazing and compaction.
- ✓ Nitrogen deposition
- ✓ Biotic exchange
- ✓ Elevated carbon dioxide (CO2) concentration (Sale et al. 2000; MEA 2005)

Figure 2: Biotic and abiotic factors that control vascular plants species distribution and biodiversity patterns along altitudinal gradients.

Tropical alpine areas experience the year-round growing season and high diurnal temperatures, with significant changes occurring in the daytime to nighttime temperature and energy budgets (Hedberg 1964; Rundel 1994). In the tropical mountain, the elevation-driven climatic difference is more important than the other biotic factors in controlling the zonation of the plant species (Whittacker 1975; Nagy and Grabherr

2009; Beierkunlein 2007; Körner 2007). Hence, this suggests that the impacts of climate change on alpine plant communities may be more detectable than in lower elevation communities (Grabherr et al. 2000).

The genetic diversity interacting with environmental conditions is the basis of the difference between organisms (Nagy and Grabherr 2009). Other factors such as the constant input of accidentals and taxa from various directions along mountain chains, habitat fragmentation, disturbance regimes, stresses and changing climatic conditions, microrelief and succession patterns also contribute to diversity (Huston 1994; Richter 2008). The mean annual temperature drops with increasing altitude in mountainous regions, and the vegetation growing period is extended. Because of the ascending air masses, precipitation increases rapidly with altitude while falling steadily after midaltitude.

Some studies directly compare the drivers of richness and endemism in mountain islands or other island-like systems and true islands (Itescu 2018, 2019; Steinbauer et al. 2016a, 2016b), and some have tried to explain the similarity and the insularity parallels between islands and "sky islands." However, recently Flantua et al. (2020) challenged the direct parallels rarely go much beyond the observation that mountaintops are isolated from one another, as are actual islands. The most substantial commonality between true islands and mountain islands is their high variability of isolation in space and time. They further argued that isolation on endemism results from multiple ecological and evolutionary processes of different intensities. For instance, higher isolation levels are reflected in reduced levels of gene flow, resulting in the potential for allopatric speciation and genetic drift (Itescu 2018, 2019; Steinbauer et al. 2016a; Rahbek et al. 2019a, 2019b).

4. Remote Sensing and Mountain Biodiversity

Remote Sensing and Geographic Information systems (GIS) are powerful tools to calculate and analyze past, present, and future changes since computers and computational software offer the possibility to simulate developments of landscapes within a framework that did not exist before (Beierkuhnlein 2002b). The last five decades witnessed a rapid increase in the use of geospatial information and tools in climatology, ecology, geography, biogeography, and other relevant sciences. These new technologies have been applied for change detection in remote landscapes such as mountains, glacier monitoring, and natural hazards detection and monitoring (Wegmann et al. 2016).

Remote Sensing is the science of identifying earth's surface features and estimating their geological and biophysical properties using electromagnetic radiation as a medium of interaction (Navalgund et al. 2007; Campbell and Wynne 2011; Jensen 2015). Remote Sensing images provide information that looks back and forth in time and space, can cover a large swath of land, and enables rapid monitoring of biodiversity change *ex-situ* (Jensen 2015). The products are an effective tool for landscape pattern analysis, such as habitat connectivity and fragmentation, and its implication for biodiversity and various structural aspects of individual ecosystems (Innes and Koch 1998). Landscape elements can be incorporated from plot to landscape to a regional and global scale into such studies (Wegmann et al. 2016). Besides, it is a surrogate indicator of spatial and temporal biodiversity patterns change detection. It provides inexpensive and verifiable means of deriving complete spatial coverage of environmental information for a large area in a consistent manner that may be updated regularly (Campbell and Wynne 2011).

The ample geospatial information and advances in analysis tools can support data needs for biodiversity conservation, monitor change in biotic conditions and disturbances. Furthermore, it can be applied to track anthropogenic threats to biodiversity, map land cover and vegetation three-dimensional structure, assess primary productivity dynamics, and monitor species and their migratory roots (Innes and Koch 1998; Navalgund et al. 2007; Jansen 2015; Pettorelli et al. 2014).

Remote Sensing and geospatial analysis tools are becoming part of the standard toolkit for ecologists, geographers, biogeographers, and climatologists, especially those working at larger spatial scales or seeking to understand the broader context (Pettorelli et al. 2014). Integrating these tools with ecological modeling algorithms opens new perspectives for quantification and precision of progress.

Since the 1970s, the data acquired from Remote Sensing has improved spatial, spectral, temporal, and radiometric resolution because of improvements in observation technology (Wegmann et al. 2016). Currently, large volumes of valuable information are available to those working at all scales, finer-grained plots, and landscape scales. At the same time, spatial analysis tools such as GIS, Quantum GIS (QGIS) (https://qgis.org), R-project (https://r-project.org), and others have shown a drastic increase in their computational abilities. The growth is most recently enabling the integration of geospatial information from multiple platforms, including the growing Open Sources Software (OSS).

5. Statement of the Problem

Ethiopian mountains have been settled and cultivated for an exceptionally very longtime (Getahun 1984; Gebreegziabher 1988; Grepperud 1996; Darbyshire et al. 2003; Hurni et al. 2010). Hence, the landscape is highly affected by human activities. Bare hills, small patches of forest, and overgrazed grasslands are characteristic features of the country's geography (Gebreeziabher 1988, 1990; Messerli et al. 1990; Hurni et al. 2010). All over the country accessible, productive areas have been transformed and utilized for subsistence farming. However, high altitude driven unfavorable climate and precipitous slopes related inaccessibility has been a limiting factor for human exploitation of some parts of the mountains (Hurni et al. 2010). The remaining original vegetation is found confined to the ecosystems that are extreme and inaccessible, "protected areas," and some sacred places close to churches and monasteries (see Getahun 1984; Gebreegziabher 1988; Hurni et al. 2010; Aerts et al. 2016; Orlowska and Klepeis 2018).

The existing environmental relationships that shape mountain ecosystems' stability and instability are expected to change in response to the synergistic impacts of climate and LULC change on the altitudinal patterns of biodiversity **(Manuscript #4).** The interrelation between LULC and climate change is discussed in Olson et al. (2008), Lambin et al. (2003), Spehn et al. (2011). Sala et al. (2000) and MEA (2005) identified five primary drivers of terrestrial biodiversity loss across global biomes. All agree LULC change to be the main threat to terrestrial ecosystems at a local level, followed by climate change, nitrogen deposition, biotic exchange, and elevated carbon dioxide (CO_2) concentration. Within a mountain's environmental, climatic and other gradients the impacts of these drivers are going to be felt at different scales and magnitudes.

In the Bale massif, how individual species, functional groups, entire communities, and ecosystems react to the synergistic impact of climate and LUCC change needs to be investigated in depth. Earn et al. 2000; Sala et al. 2000; Olson et al. 2001; Lambin et al. 2003; Röder et al. 2008; Olson et al. 2008, Hurni et al. 2010 underline the need to combine human-environmental systems across space at multiple scales, from the global climate to regional to local decision making **(Manuscript #1, 2, and 3)**. The two main drivers of biodiversity change are discussed below.

5.1 Land Use Land Cover (LULC) Change

In the past, Ethiopia has failed to protect its natural resources considerably. Gebreegziabher (1991), Jacobs and Schroeder (2001), Stephens et al. (2001); Taddese (2001); Amente 2005; Hurni et al. (2010); NBSAP (2005) and Hailu et al. (2018) discuss the failures of past policy, political pressure, and some of the causes of natural resources mismanagement and biodiversity loss in Ethiopia. Rapid population growth driven demand for land (settlement, infrastructure, and farmland), land degradation, scarcity of arable land, deforestation (fuelwood collection, charcoal production, land clearing for agriculture etc.), excessive livestock population induced overgrazing and soil compaction, soil and genetic erosion, and poaching and failed protected area policies are some of the significant causes of biodiversity loss.

LULC change is the main threat, and the primary driver of biodiversity patterns change, including ecosystem function and services they provide, and an important indicator of habitat loss, niche shrinkage, and fragmentation at a local level (Earn et al. 2000; Sala et al. 2000; Röder et al. 2008). The direct impacts of LULC change are immediate and affect the Earth's radiative forcing, and alter the land surface roughness and albedo. It affects exchanges of sensible heat, latent heat and carbon dioxide, and other greenhouse gases between the land surface and the atmosphere, thus contributing to climate change (Lambin et al. 2003). In addition, it results in habitat loss and fragmentation, which are the leading causes of species extinction (Beierkuhnlein 2002a).

In the Bale Mountains, habitat loss and simplification, and fragmentation of natural areas affect the already threatened biodiversity, especially the endemic. Anthropogenic disturbances along the lower elevation of the mountains observed since the early 1980s (Hillman 1986). The natural habitats have been transformed and fragmented due to population growth, which has driven demand for settlement, agricultural mechanization, and residential and infrastructure expansion (Kidane et al. 2012). Other causes of biodiversity loss include neglect and lawlessness during political instability and government transition, e.g., (Jacobs and Schloeder 2001; Kalpers 2001), and significant fire incidents in 2000 and 2008 (Wesche et al. 2008; Johansson and Granström 2014) resulted in severe biodiversity loss. The massif, including inside the territories of BMNP, has been under increasing human pressure. In the 1980s, approximately 2500 people lived within the BMNP boundaries (Hillman 1986). The number increased dramatically to about 40,000 in 2007 (FZS, 2007). The 1985 and 2003 government villagization and settlement program are one contributing factors (Amente 2005).

In the Bale Mountain areas, the impacts of the recent socio-economic change due to the intensification of human activities are more immediate and more pronounced (**Fig. 3**). Areas along the major roads are fragmented and are frequented by traffic (vehicles, humans on foot, and horseback). Until recently, the wheat and barley farms were at comparatively lower altitudes, while garlic, onion, and other vegetables were at higher altitudes. Recently, crop production expanded up to elevations 3500m asl, and intensified livestock grazing (cattle, goats, and bovines) is becoming common on the plateaus, even around the summits (Kidane et al. 2019).

Figure 3: The recent LULC change in the Bale massif and its implication for the unique Afroalpine flora and fauna: a and b) Domestic animal grazing and compaction, one of the serious causes of biodiversity loss on the Afromontane and Afroalpine plateau, c) Intentional fire is common in the BMNP and surrounding areas. Farmers burn their farmland to burn farm residue, suppress weeds, and boost farm productivity, d and e) Road construction using heavy machinery (infrastructural expansion), and the trees on the slopes of the mountains are buried by the debris, f) Exotic plant species introduction: Plantation of *Eucalyptus globulus* and *Juniperus Spp.*, and g, h, and i) Habitat fragmentation is endangering wild animals such as *Tragelaphus buxto*ni (Mountain Nyala), and *Phacochoerus africanus* (Warthog) more than ever. Photo: Yohannes O. Kidane 15-30.03.2011.

In the Bale massif, biodiversity has been persistently depleted since the 1960s and is currently under imminent danger. Plenty of evidence indicates human pressure in the Bale Mountains area (Stephens et al. 2001; Johansson and Granström 2014; Gil-Romera et al. 2019; Ossendorf et al. 2019). The main threats to biodiversity conservation in the massif are of anthropogenic origin. Population growth accompanied by inadequate economic policies has deepened poverty, widened income inequalities, and forced rural people and others to exploit biodiversity at no longer sustainable rates (Stephens et al. 2001; NBSAP 2005).

Population Growth

Population growth is leading to increasing demand for food, energy, and infrastructure. In Mountain regions, anthropogenic pressure such as settlements, agricultural land expansion, and infrastructure in and below the Afromontane and Afroalpine belts endanger mountain biota more than climate change in many regions of the world (Earn et al. 2000; Sala et al. 2000; Jentsch and Beierkuhnlein 2003; Spehn et al. 2011; Röder et al. 2008). It is primarily responsible for the observed rapid habitat loss and fragmentation (Sala et al. 2000; Röder et al. 2008). In the seminatural ecosystems, fragmentation of habitats will restrict the dispersal of species and mobility. Thus, it will affect the potential of species and ecosystems adaptation (Jentsch and Beierkuhnlein 2003).

The pristine landscape is getting converted due to rapid population growth. According to UNDP Human Development Report (HDR) (2020), Ethiopia's human development index is 0.485, putting the country in the low human development category, positioning it at 173 out of 190 countries and territories. However, according to UNDP, over the last 20 years, the country's HDR value increased from 0.283 to 0.463, increasing 63.5%.

Ethiopia is the second highly populated county in Africa. Over the past half a century, the population of Ethiopia has increased from 7 million in 1940 to 107 million in 2019 (HDR 2020). The current population is projected to reach 173 million by the year 2050 (HDR 2020). The population is mainly rural, relying on subsistence agriculture, with only 16.5% living in towns and cities (Hurni et al. 2010). Besides, the mountainous landscapes host large concentrations of over 83.5% of the total population and livestock (Amsalu and de Graaff 2006; Hurni et al. 2010).

The need to accommodate the population growth and the recent economic transformation: mechanization of agriculture, infrastructure expansion, and intensification of land investments, are causing the conversion of the pristine habitat (Kidane et al. 2012). The population growth is also inviting domestic animals and their ailment to the park's wild animals. The population of the Ethiopian wolf (*Canis simensis*), a critically endangered canid, has severely declined from 1989 to 1992 due to rabies epizootics (Sillero-Zubiri and Macdonald 1997; Stephens et al. 2001). Further, interbreeding between dogs and Ethiopian wolf is another sustained problem brought to the area with increasing human presence (Laurenson et al. 1998).

Agriculture and Land Grabbing

Subsistence agriculture is the dominant farming system in the county. Agriculture in the Ethiopian highlands began several thousand years ago, leading to disproportionate impacts on natural resources over time (Getahun 1984; Taddese 2001; Gebreegziabher 1991). Since the early 20th century, the land use and land cover change have intensified. Consequently, land degradation and loss of productivity have accelerated (Gebreegziabher 1991; Taddese 2001; Amsalu and de Graaff 2006). Recently, foreign investment related land grabbing has been exacerbating the situation (Ingebretsen 2015).

There are no dwellings above the treeline in the Bale massif due to the harsh nighttime climate, but there are scattered homesteads in the forests below and surrounding Gaysay grasslands (Stephens et al. 2001). Since 1983 there is an increasing presence of domestic stock (Stephens et al. 2001; Kidane et al. 2019). The heathlands and the Afroalpine plateau are the primary pasture area. The local livelihoods depend on livestock, primarily cattle, sheep, and goats. In the Afroalpine plateaus cattle and other domestic stocks graze in small herds (up to 20 animals).

Some recent reports from Northern Ethiopians Mountain suggest that people there are now tilling marginal lands: barley is sown up to 4,100m asl on slopes steeper than 45° making the area the highest altitude at which barley is cultivated anywhere in the world (NBSAP 2005; Hurni et al. 2010). Though not particularly investigated, there is observed upward expansion of farmland in the Bale Mountain massif (Kidane et al. 2019).

Soil Erosion

The country's considerable number of livestock has resulted in overgrazing, soil compaction, soil erosion, and land degradation at a national level, which directly affects the country's biodiversity. Ethiopia has the highest number of domestic livestock in Africa. CSA (2009) estimated 49.3 million cattle, 25 million sheep, and 21.9 million goats. Of the total cattle population, only 30% are in the lowlands (Taddese 2001; Amsalu and de Graaff 2006). The Bale zone is known for its cattle, sheep, goat, and bovine population. The current average national cattle, sheep, and goat population per km^2 are estimated to be 71, 33, and 29, respectively (CSA 2009).

In the Bale Mountains, overgrazing has increased the competition between livestock and wildlife. Habitat loss threatened the Afroalpine range due to high altitude subsistence agriculture and livestock overgrazing (Amente 2005). Thus, in 2002, the livestock in a discrete area of the Bale Mountains reached an unprecedented density of 314 animals per km^2 (Amsalu and de Graaff 2006). In addition, steep slopes of the high mountains, deforestation, and short-lived showery rain are in the grip of accelerated erosion, genetic erosion through a mass extinction of endemics. Besides, the recent increase in trekking tourism is also contributing to soil erosion.

Deforestation

Ethiopia's population heavily depends on biomass fuel for domestic energy production (Woldeghiorgis 2002). The biomass-based fuel supply accounts for 92% of the country's total energy (Guta 2012). Household consumption constitutes 89% of the total energy supply, followed by agriculture, transport, and industry account for only 7.2% of total energy consumption (Woldeghiorgis 2002).

For centuries the population relied solely on traditional biomass energy sources, such as fuelwood, charcoal, crop residues, and animal dung (Amente 2005). Hence, the energy demand pushed deforestation, and the absence of substitutes for the traditional energy sources are some of the leading causes of habitat degradation, surface structure, and biodiversity loss. Deforestation is resulting in the local extinction of some species, genetic erosion, and decline of woody species (Gebreegziabher 1991). In the Bale massif, logging within and the periphery of the park is prohibited. However, the irresponsible, illegal logging results in habitat loss and exposes the fauna to habitat loss and illegal hunting (Amente 2005; Hunri et al. 2010). The Oromia region supplies about 40% of biomass resources energy (Guta 2012).

Fire

Fire is dependent on critical factors such as vegetation cover type, aspect, slope, wind direction, and substrate build up. The average fire return interval in the Bale mountains is about ten years (Assefa et al. 2011; Johansson et al. 2012). The Bale Mountains area inhabitants used fire as a natural resources management tool. Even though intentional burning is illegal in the area, fire happens due to both natural processes and humans. The locals burn the *Erica* woodlands to rejuvenate pasture, control toxic caterpillars and reduce predators (mainly common jackal (*Canis aureus* L.), spotted hyena (*Crocuta crocuta* Erxleben), and leopard (*Panthera pardus* L.) attacks (Johansson et al. 2012). At the midaltitude and lowlands farmers ignite fire to remove farm residue, weed, and pest control and boost farm productivity.

However, some plant species, such as *Erica* spp., regenerate rapidly by sprouting again from lignotubers (Wesche et al. 2000). Fire in the Ericaceous belt happens due to the highly flammable nature of *Erica* due to its small leaf size, fine branching structure, and the persistence of dead branches (Gizaw et al. 2013). Besides, the high calorific value of their foliage increases their flammability (Wesche et al. 2003; Johansson et al. 2012; Gil-Romera et al. 2019). Recently, increased natural fires and droughts have been observed in the Bale massif (Wesche et al. 2000, 2003; Assefa et al. 2012).

Failed Protected Area Policy, Lack of Ownership, and Citizens' Stewardship

In the 1980s, a poorly planned expansion of mechanized state farms in the lowland left little room for pastoralists, except at higher altitudes (Stephens et al. 2001). Recently, land grabbing (Ingebretsen 2015), expansion of commercial coffee farms on the lower peripheries of the moist tropical rainforest, and infrastructure expansion within the territories of the BMNP, still result in biodiversity loss and LULC change.

Jacobs and Schloeder (2001) identified that people became irresponsible and hostile to the environment during government transition and armed conflict. Wild animals have been hunted for subsistence use, as status symbols, income generation, as a buffer during famines, as food by armed groups, and during political upheavals. For example, during a brief period of unrest associated with the transition between governments, firearms because readily available, and wildlife became the target for expression of resentment over restrictions and prevention of activities such as settlement, grazing, cultivation, and collection of fuelwoods (Stephens et al. 2001).

National phenomena hold true for the Bale massif, too. For example, the endangered mountain Nyala (*Tragelaphus buxtoni*) and other species bohor reedbuck (*Redunca redunce*), menelik's bushcuck (*Tragelaphus scriptus meneliki*) and the endanger Ethiopian wolf (*Canis simensis*) were speared or shot during the 1991 government transition (Sillero-Zubiri and Macdonald 1997; Jacobs and Schloeder 2001).

5.2 Climate Change

Anthropogenic modifications of biogeochemical cycles lead to substantial responses of the physical and chemical properties of the atmosphere (Jentsch and Beierkuhnlein 2003). Contemporarily, the leading causes of climate change are mainly emissions from fossil fuel burning, and agriculture and food production are happening far beyond the natural ecosystems can tolerate. The recent climate change will be faster than anything experienced in tens of millions of years (Lovejoy and Hannah 2005). The global mean temperature has been rising at 0.25°C per decade, and over the last fifty years, it has increased by around 0.74°C (Colwell et al. 2008; IPCC 2014) of Earth's maximum temperature in the past million years, exceeding the Holocene maximum (9000 to 5000 yr B.P.) of the current interglacial (Hansen et al. 2006). Moreover, the rate at which emissions are increasing exceeds that in our baseline scenario for the present decade (Peters et al. 2012).

Climate change-related warming is expected to impact plant diversity and distribution at all levels starting from single species to biomes (Parmesan 2006). It further will result in habitat quality deterioration and instability which could lead to the loss of species, alteration of species diversity, abundance, and distribution (Enquist 2002; Davis et al. 2005; Malcolm et al. 2006; Lovejoy 2008; Jump et al. 2009; Kreyling et al. 2010). At all levels of life organization warming will lead to habitat degradation, deterioration, instability, alteration, and modification, which is causing biodiversity loss among other alterations of plant diversity and distribution at all levels starting from single species to biomes (Enquist 2002; Davis et al. 2005; Malcolm et al. 2006; Parmesan 2006; Lovejoy, 2008). Others Rahbeck et al. (2019a) warn that the role of mountains as refugia for biodiversity may come under threat with recent climate change.

According to future climate change projections, impacts of global warming will show a distinct geographical pattern with the changes being greater over land, high latitudes, and elevations (Barry and Seimon 2000; Hannah et al. 2002; Lovejoy and Hannah 2005). Recently, global warming impacts have been observed on mountains ecosystems, i.e., surface temperature increase and glacial melting over the last century across global mountains (Barry and Seimon 2000; Hannah et al. 2002; Nogues-Bravo et al. 2007, 2012). Glaciers are near extinction in African mountains, e.g., the receding of glaciers Mount Kilimanjaro (Chan et al. 2008). Species extinction that happens as a singular event affects only the isolated population. Yet, when specific biotypes such as Afroalpine ecosystems are affected, the whole species pool and range of endemics of the landscape will be affected (Personal communication Beierkuhnlein, 2021).

On mountain ecosystems, climate change will induce thermal isotherm shifts, which can disrupt the stability of Afroalpine ecosystems affecting the unique plant diversity, distribution, and species richness, leading to unexpected species and functional groups reorganization and massive endemic extinction (Malcom et al. 2006; Kreyling et al. 2010; Kidane et al. 2019). Altitudinal gradient/range shift analysis is widely applied to assess the role of climate change on plant diversity and distribution. It is a powerful method for testing biota's ecological and evolutionary responses to geophysical influences, such as temperature changes (Beierkuhnlein 2007; Körner 2007; Nagy and Grabherr 2009) **(Manuscript #2).**

The mountain species are mainly due to species' limited ability to adapt to new environmental conditions and fast changes in ecosystems structure and function as erosion control, variation in water flow, surface structure loss, slope instability, nutrient cycling, and biomass production alters (Beierkuhnlein 2002a). However, species and taxa will respond to climate change independently due to mountains' topographic, climatic, and geological complexity (Huston 1994; Sala et al. 2000; Lovejoy and Hannah 2005; Diaz et al. 2006; Körner and Hiltbrunner 2021).

Small shifts in the thermal isotherm along altitudinal gradients may compel species to remain within their tolerance limits and adapt (persist locally e.g., in refugia), move to novel environmental conditions (migrate to more suitable places), change phenotypically (through plasticity or evolutionary adaptation), change abundance, or go extinct (Enquist 2002; Davis et al. 2005; Dawson et al. 2016). Warming is likely to result in altitudinal range shifts via dispersal or migration and local loss of populations, which means extinction in the case of spatially restricted endemic species (Walther et al. 2002; Malcolm et al. 2006; Steinbauer et al. 2018) **(Manuscript #3)**. In the mountains, ecosystems will result in displacement of ecosystem boundaries and reduction in the total area of the Afroalpine habitat (Kidane et al. 2019; Pihl et al. 2019). Yet, unlike past migrations, in the future, species will find factories, freeways, farms, and urban settlements in their path (Parmesan and Yohe 2003; Lovejoy and Hanna 2005). These phenomena have been documented and anticipated to continue.

6. Scope of the Study and Significance for Biodiversity Conservation

This study investigates the synergistic impacts of drivers of biodiversity change mainly climate and LULC change, and their implication for biodiversity conservation and ecosystem functioning in the Bale Mountains of Ethiopia. The aim is to contribute to the conservation management of the Bale Mountains' biodiversity and further instigate discussion on the significance of biodiversity conservation and management in remote landscapes. In addition, I passionately believe the immense biodiversity harbored in such remote landscapes is important and knowledge about the spatial distribution and richness patterns of biodiversity is crucial for its further exploration, sustainable use, and conservation management planning. The study further investigates various aspects of plant diversity in the face of global change to provide further insight into the potential role of climate and LULC change in structuring the massif's vascular plants diversity from plot to the landscape.

The main threat to biodiversity comes from rapid global change driven by unchecked human population growth. Recently, it has resulted in mass extinction or faster than the usual reduction of species, degradation and simplification of natural habitats, and impairment of ecosystem services and functions (Myers et al. 2000; Sala et al. 2000: Olson et al. 2001). Hence, the United Nations Convention on Environment and Development (UNCED) in Rio de Janeiro in 1992, besides adopting mountains in its sustainable development agenda, comes out with the binding law, the Convention on Biological Diversity (CBD). Since its adoption, the treaty has played an increasingly key role in engaging policy and supporting participatory political discussions.

The CBD article 2 defines biodiversity as "*the variability among living organisms from all sources including, inter alia, terrestrial, marine and others aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems.*" This definition is universally adopted; however, many other studies developed it further. For example, Huston (1994) "*it is the number, abundance, composition, spatial distribution, and interactions of genotypes, populations, species, functional types and traits, and patterns of nature up to landscape level.*" further refined it and added, "*and ecological diversity overall spatial and temporal scales.*" These definitions indicate that diversity includes the different organization levels from genetic to organism up to species, taxonomic group, communities, and even ecosystems and landscapes (Beierkuhnlein 2002a).

The aims of the convention on biodiversity are conservation, sustainable use, and fair and equitable sharing of its benefits. To achieve these goals, information on the broad scale of interaction such as human-biodiversity, climate change, lowland highland interactions, local drivers of biodiversity pattern change and loss, and their implication to mountain biodiversity is critical. These areas have hardly been discussed and investigated in the Bale Mountains. Similar to many other tropical mountains in Africa and Asia (see Parmesan 2006), Afroalpine ecosystems are also less studied in terms of the synergistic impact of climate and LULC change from plot to the landscape. Besides, biodiversity is vital for the human wellbeing, survival, and sustainability of life on earth. If it is not handled with fairness, ethics, equity, and responsibility, it can be a source of conflict, ultimately leading to the annihilation of many species, including human beings (Kibert et al. 2010).

Ethiopia is a signatory and party to the CBD. Since it first becomes a party to the convention in July 1994. Ethiopia has passed Biodiversity Action Plans for several fields where biodiversity is affected, e.g., agrobiodiversity and forestry. It has developed a biodiversity action plan, national assessment, and research program. One of its recent actions includes the Strategic Plan 2011-2020 to achieve the 2020 Aichi Biodiversity Targets. Moreover, the government has devised a Climate Resilient Green Economy (CRGE) Strategy, which will be based on four pillars, namely: agriculture, forestry, power, and transport, including industrial sectors and buildings. As part of the CRGE Strategy, REDD+ will also be implemented as a policy incentive to promote forest and biodiversity conservation and enhance carbon stocks.

The unique biodiversity is under immediate threat from the coupled impact of local intensification of human activities and climate change. This alteration of natural habitats affects ecosystem processes and changes the environment's biophysical attributes, leading to a deteriorated biodiversity and loss of species. Similar to the rest of the tropics (see Colwell et al. 2008), in the Bale Mountains, species upslope range shifts are expected to happen because of the shallow latitudinal temperature gradient. Though science has reacted by intensifying research and expanding the scientific discourses globally, studies that focus on species diversity, richness, and endemics along an altitudinal gradient and climate change impacts on future species distributions are rare.

7. Hypothesis and Research Questions

Detailed plot to landscape biodiversity pattern analysis that incorporates field sampling, large geospatial data, and uses geospatial analysis tools is a promising approach to understanding the biodiversity-environment relationships considering synergistic impacts of climate and LULC change. In addition, considering the synergy and its severity, the complex relationships of species-species, species-functional type, functional type–functional type relation, and their interaction with the environment need a comprehensive approach. Yet, the degree of the synergistic impacts and their implication for biodiversity are not fully explored.

1. Global change drivers such as population growth induced intensification of human activities, increased deforestation and agricultural expansion, fluid natural resource conservation policies, and other socioeconomic issues are resulting in enormous biodiversity loss besides climate change. Therefore, there is a measurable interlinkage between socioeconomic issues and climate change drivers of biodiversity loss across Afromontane and Afroalpine ecosystems. The synergistic impact can be modeled and assessed across these ecosystems.
2. Landscape level LULC change is the leading cause of biodiversity loss, and it can be assessed. The leading socio-economic drivers of LULC change and the degree of the loss can be quantified and identified. The vast geospatial information acquired from Remote Sensing has the potential and can be utilized to detect biodiversity pattern change along elevational gradients over a long time and a sizeable spatial swath. Over the last sixty years, the Bale massif has been exposed to increased human activities. The change in environmental conditions, particularly LULC change and its implication for biodiversity conservation management in general, vegetation cover classes analysis, plant species richness, and distribution pattern can be assessed and quantified.
3. Remote Sensing, Geographic Information systems (GIS), and other geospatial information and tools can supplement species information acquired from plots and other biodiversity data sources to monitor biodiversity patterns. The comprehensive database is useful to model the current and future distribution of species and help improve the predictive performance of Species Distribution Models (SDMs). Besides, it is a sound contemporary approach that predicts the effects of climate change-induced warming on mountain biodiversity, especially to model some of the major cover classes, such as the Ericaceous vegetation.

4. The vascular plant diversity and distribution patterns in the Bale Mountains can be modeled. Across the massif plant species, particularly those Afroalpine endemics, are experiencing change and will continue to experience impacts of climate change. The impact of the projected climate change on vascular plants, particularly endemics diversity and distribution, can be modeled and identified. Such findings are important to improve the conservation and management of biodiversity.

Based on the above hypothesis, we raise and address the following questions:

1. What does the study of the synergy of climate and LULC change look like across Afromontane and Afroalpine ecosystems? What is its implication for biodiversity conservation and management? What can be done to reduce the impacts of synergistic impacts of climate and LULC change on Biodiversity? What is the possible socioeconomic implication, and how should science and policy responses to it?
2. How has the biodiversity pattern (land cover change, fragmentation, habitat simplification, etc.) and the massif natural vegetation changed gradually across the landscape? Was there any significant LULC change in the Bale Mountains massif over the last fifty years? If so, what are the main drivers of this pattern change? And, what causes the difference, and what is its implication for the associated fauna and flora diversity?
3. What are the projected future climate change impacts on some dominant cover classes, e.g., the Ericaceous vegetation? What is its implication to the associated flora and Afroalpine habitat?
4. What does species diversity and distribution look like along the massif? What are the impacts of projected future climate change on species diversity and distribution along altitudinal gradients? What is the impact of climate change on endemic diversity and distribution under the projected climate change?

8. Objectives

The overall objective of this thesis is: *“to study the long-term impacts of the main drivers of biodiversity loss and change on the spatial and temporal patterns of biodiversity and ecosystems functions along altitude gradients of the Bale Mountains of southeastern Ethiopia, utilizing current geospatial information and analysis tools.”* This thesis tries to enhance the understanding of the threat posed by the synergy of climate and LULC change in the Bale Mountains and beyond by utilizing Satellite imagery, GIS, and statistical modeling approaches by raising coupled natural and social science issues.

Specific objectives are:

1. To assess the degree of LULC change and carry out biodiversity spatial patterns analysis using fifty years-long satellite images and identify the main drivers of the change in the Bale Mountains area. **(Chapter 1** (Manuscript #1)**).**
2. Demonstrating direct consequences of warming prompted thermal isotherm shift for the diversity, abundance, and distribution of some of the major cover classes, such as Ericaceous vegetation along the elevational gradients, and its implication for associated flora Afroalpine ecosystems. **(Chapter 2** (Manuscript #2)**).**
3. To analyze altitudinal patterns of diversity and richness gradients of vascular plants and test for range shift of thermal isotherms, which may lead to upwards shift, adaptation, or extinction of vascular plant species, especially those of endemics **(Chapter 3** (Manuscript #3)**).**
4. To assess the potential consequence of the synergistic impacts of climate and LULC change on Afroalpine ecosystems in general and its implication for vascular plant species distribution, diversity, productivity, and richness patterns across the massif. **(Chapters 4** (Manuscript #5)**)**.
5. To assess and document the status of the Bale Mountains Afroalpine ecosystems and evaluate the role of Anthropogenic impact on the mountain biota in general and on the alpine and subalpine area.
6. To contribute (1) to frame conservation management strategies for biodiversity in the face of climate change and increasing human activities; and (2) to add a voice to the calls for bringing international attention to recognizing the Afroalpine habitat as a globally significant biodiversity hot spot.

9. Material and methods

9.1 Study Area

The Bale Mountains of Ethiopia

The Bale Mountains are located 400 km south of Addis Ababa, in southeast Ethiopia in the Oromia regional state, among those Ethiopian high mountain chains situated in the Great East African Rift Valley (**Fig. 4**), between 06°29′ N, 39°03′ E, and 07°10′ N, 40°00′ E. The mountains comprise one of the most extensive high-altitude plateaus of altitude above 3,000 m asl, a contiguous mountain massif of over 2,600 km^2 in Africa, and one of the last remaining pristine Afroalpine biodiversity hotspots on the continent (Hillman 1988; Laurenson et al. 1998).

The Bale Mountains National Park (henceforth BMNP) was established in 1971 to protect the Afroalpine endemic flora and fauna, covering above 2200km^2 of Afromontane and Afroalpine habitats located within the mountains (Hillman 1986,1988). These mountains are one of the last remaining pristine Afroalpine biodiversity hotspots in the tropics and one of the last remaining habitats for Bale endemic flora and fauna. The BMNP alone harbors at least 111 or 18.8% of the national endemic flowering plant species (with ten restricted to the park limits), 20 or 26.5% of the national endemic mammal species, and 9 or 53.3% of the national endemic birds. In addition, the endemic plants' density is 2.5 taxa per 100km^2 (Friis et al. 2005). The southern slops, it is covered by subalpine tropical rainforest forests from approximately 2,700m up to the treeline at 3500m, where the tree formed Erica spp. (~15m tall) revert to a shrubby heathland.

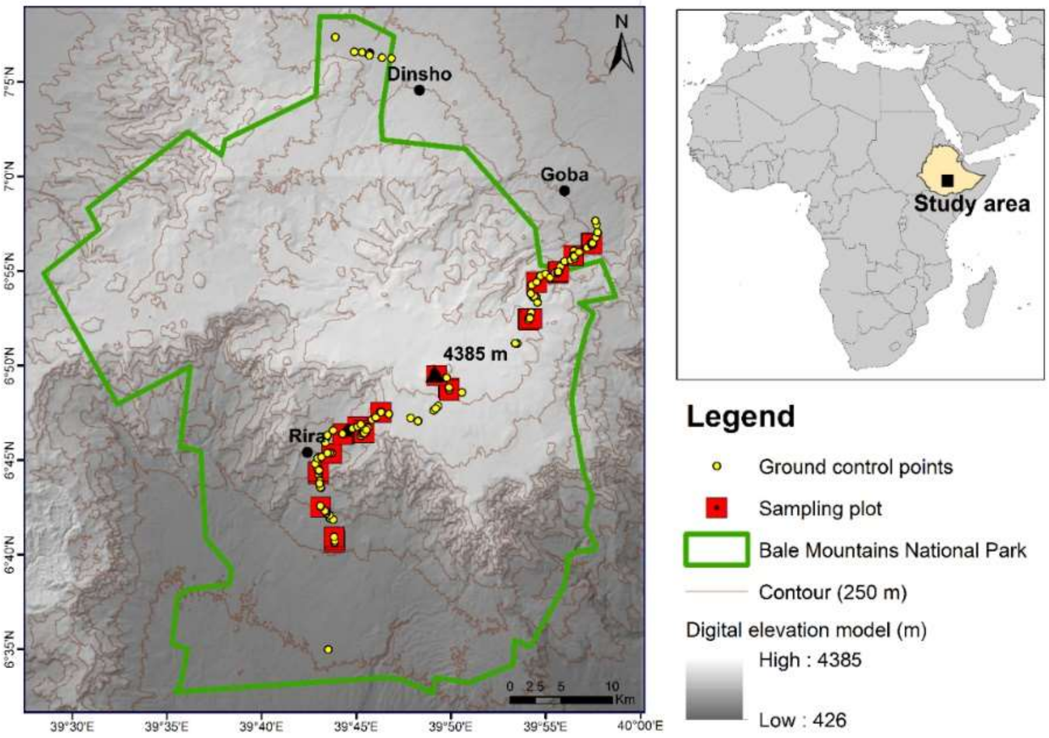


Figure 4: Map of the study area, including the sampling plots transect location, ground control points, and the Bale Mountain National Park (BMNP) boundaries.

The Harenna escarpment that runs from east to west divides the mountain into North and Southern parts. On the southern slopes of the massif, the Harenna escarpment is known for the distinct altitudinal zonation of the Afromontane forests, including the most extensive Ericaceous vegetation on the continent (Assefa et al. 2011). The uppermost part lies the Sanetti plateau, an isolated area covering 211km^2 at an altitude of about 4000m asl bordered by an abrupt escarpment to the south. Three summits immerge above 4100m asl on the plateau: Tuilu Deemtu 4385m asl (the second-highest point in Ethiopia), Batu 4307m asl, and Konteh

4132m asl.) of total area of 99.1km^2 reach elevations beyond 4100m asl, while the most significant part of the plateau is characterized by homogenous topography (Kidane et al. 2019).

The Bale Mountains harbors unique biodiversity with many endemics, some of which are threatened with extinction (Assefa et al. 2011). They generate numerous natural processes vital for human existence and support an essential genetic resource reservoir that is still partly unknown (Hillmann 1988; Uhlig 1990). The mountains are of global significance because of the rare, endangered mountain endemics found across all taxa and habitat types.

The BMNP are high a priority conservation area of global significance. The Mountains are recognized as part of the Eastern Afromontane biodiversity hotspot by Conservation International (Williams et al. 2004) and are among the 34 biodiversity hotspots and are listed by UNESCO as a tentative world heritage site and biosphere reserve (Mittermeier et al. 2004). Further, they are within the range of Endemic Bird Areas analysis of BirdLife International (Stattersfield et al. 1998). Nevertheless, given their significance, they have received little international attention.

Geology and Geomorphology

The Bale Mountains' geology is characterized by a high-altitude volcanic plateau over much older volcanic material formed during the spreading of the East African Rift Valley system (Friis et al. 2005). The landscape is fragmented due to numerous volcanic plugs, peaks, alpine lakes, and streams that descend into deep rocky gorges on their way to the lowlands (Umer et al. 2007). Bare rocky ground and gravely exposed soils are characteristic features of the Plateau. The north and northeast are deeply dissected valleys descending to the northern slope, while to the west, lava flows form spectacular bluffs (Bonnefille 1983; Osmaston et al. 2005).

The petrography is dominated by alkali basalts and tuffs, with occasional rhyolites (Uhlig and Uhlig 1991). Soils tend to be shallow, gravelly, and recently derived from volcanic rock exposed since glacial retreat (Sillero-Zubiri and Macdonald 1997). The topsoil is stratigraphically youngest units derived from the Miocene basalt and trachyte lavas that lay over Mesozoic sediments (Umer et al. 2007). They consist of a relatively silty loam of reddish-brown to black (Woldu et al. 1989). The mountains were locally glaciated, which shaped their recent geomorphology (Osmaston et al. 2005).

Soils in the area tend to be shallow, gravelly, and recently derived from stratigraphically youngest units derived mainly from the Miocene basalt and trachyte lavas that lay over Mesozoic sediments (Umer et al. 2007). One of the most important soil characteristics is its reaction, which is correlated to base saturation, availability of metal ions and phosphorus, flocculation, etc. They consist of relatively silty loam, clay, sandy loam, and silty loam of reddish-brown to black color. Afroalpine soils of other East African mountains seem to be overall distinctly acid, on the wettest relives the soils pH values are between 4.0 and 5.5, and the peats between 3.5 and 4.5 (Hedberg1964).

Climate

The Bale Mountains are at the convergence of the wet East African and dry Northeast African mountains of southeast Ethiopia. Hence, rain comes to the Bale Mountains from two different sources, the equatorial westerly and the India Ocean monsoon (Uhlig 1990; Miehe and Miehe 1994). The climate of the mountains varies from north to south mainly due to the differences in elevation, aspect, and the influences of lowland hot air masses (Uhlig 1990). The climate is characterized by a short dry season (November to February) and an extended period of rainfall and high moisture (March to October). The mountains receive relatively high rainfall, and the weather is cloudy.

The contemporary climate within the area varies from northeast to southwest mainly due to Orographic effects (Uhlig, 1990; Miehe and Miehe, 1994). The south and southwest facing slopes are more humid with a subtropical climate, high annual rainfall (up to 1500mm/year), and the dry season lasting only about two months. In contrast, the north and northeastern parts receive 800 to 1100 mm/year of annual rainfall and a wet season from June to September. The rainfall pattern is slightly bimodal, with a peak from April to May followed by a second peak from September to October (Woldu et al. 1989) **(Fig. 5).**

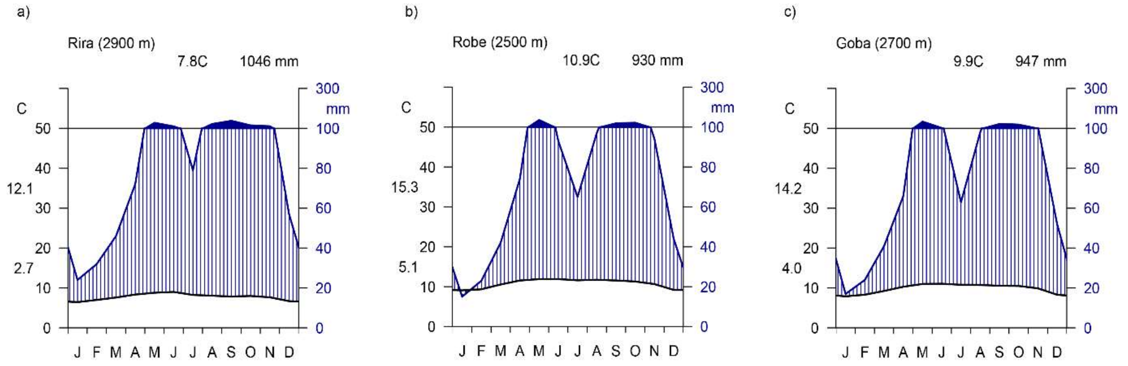


Figure 5: The thirty-year mean temperature and precipitation of Robe, Goba, and Rira derived from the worldclim climate database - http://worldclim.org/version2 (Fick and Hijmans, 2017). Rira is located on the southern part of the massif at 2900m asl. Its mean annual temperature is 7.8°C, and annual precipitation is 1046mm; Goba and Robe are located on the eastern and northeastern part of the massif at an altitude 2500m and 2700m asl with mean annual temperatures of 10.9°C and 9.9°C and average annual precipitations of 930mm and 947mm, respectively. Vertical hatching indicates a surplus.

The northern part exhibits 800 - 1,000mm of annual rainfall and a wet season from June to September. The southern part is more humid, with a subtropical climate and 1,000 - 1,500mm of annual rain (Woldu et al. 1989). Overall, precipitation increases up to 3,850m asl to a maximum at a middle altitude, which roughly corresponds to montane or cloud forest occurrence, decreasing steadily towards the summits (Hillman 1986).

The dry season is characterized by more pronounced diurnal temperature fluctuations and regular night frosts (Hillman 1986). Strong diurnal temperature fluctuations signify the Afroalpine habitats. On the Sanetti Plateau, Hillman (1990) recorded extremes of a daily temperature range of 40°C (−15°C to +26°C) during the dry season. The flora experience extreme temperature variation within a day for the whole year, experiencing "summer every day and winter every night" (Hedberg 1964). The diurnal amplitude in temperature varies between the wet and dry seasons, air and soil, bare soil and vegetated and other surfaces. The wet season is warmer at night and cooler by day compared to the dry season (Admasu et al. 2004). The coldest time of the year is the driest, and the wet season is associated with the convergence of northeast and southwest airstreams (Bonnefille 1983).

The area has recently experienced increased frequency and severity of exceptional droughts, e.g., 2000 (see Wesche et al. 2003, 2008). Paleoclimatic evidence indicated historically the mountains had experienced a high degree of climate variability and change (Bonnefille 1983; Peyron et al. 2000; Umer et al. 2007; Kuzmicheval et al. 2013, 2014). These past climatic changes and anthropogenic activities have played a crucial role in shaping contemporary vegetation.

Vegetation

The massif exhibits a steep gradient of ecological zones, evident from the spectacular zonation, which resembles other East African Mountains (Uhlig and Uhlig 1991; Friis, 1992, Friis et al. 2005; Miehe and Miehe 1994). Isolation and huge extent of the massif, historical climate variability, and topographic complexity has driven microclimate, and resulting habitat diversity has resulted in high endemism (Friis et al. 2005). The massif is a plant diversity hotspot that provides a habitat for one of the largest concentrations of endemics (Hillman, 1986).

Among the Mountain's diverse vascular plants many are of high ethnobotanical importance. For example, Yineger et al. (2007) identified 74 veterinary medicinal plant species distributed among 64 genera and 37 families, and again Yineger et al. (2008) also identified another 101 plant species, which heal 56 human ailments. Another ethnomedicinal study by Lulekal et al. (2008) in the Mana Angetu District, one of the four districts of the area, documents 230 plant species of medicinal use to both humans and animals. Most of the plants (78.7%) were used to treat human diseases yet are under threat (Yineger et al. 2008).

Vegetation structure and composition differ between the southwestern and northeastern gradients. On the southwestern transect, the vegetation changes from the moist tropical rainforest at 2000m asl (altitude of our lowest sampled plot) to the broadleaf evergreen forest at around 2800 m, to Ericaceous Forest around 3200 m asl, Ericaceous shrubland between 3600m and 4100m asl and finally to the Afroalpine shrub and grassland habitat at the Sanetti plateau.

On the Northern and Northeastern parts in the altitudes that extend from 2500 m to 3400 m asl are the *Juniperus, Hypericum*, and *Hygenia* Woodland. A mixed *Juniperus* forest mainly dominates this habitat. It is primarily *Hagenia* and *Hypericum* zone. It is dominated by 12–18m tall *Hypericum revolutum* and *Rapanea melanophores*, *Erica arborea* forests, and *Hagenia abyssinica* up to 25m tall. *Schefflera abyssinica*, *Maesa lanceolate, Rapanea simensis, Solanecio gigas,* and *Rosa abyssinica* are also common (**Fig. 6a**).

On the Southeastern part, the area south of Goba, around 2700m asl is dominated by small rainfed agriculture, heavy livestock grazing and browsing grassland and shrublands, and vast plantation of exotic tree species *Eucalyptus* and *Cypresses*. At higher altitudes agricultural land encroaches up to around 3500m asl; small-scale Garlic plantations may reach even higher altitudes **(Fig. 6b-c)**.

Figure 6: Northeastern, eastern, and southeastern parts of the Sanneti plateau at an altitude above 2700m asl: a-b) isolated remnant of *Juniperus procera*, *Hagenia abyssinica, Hypericum revolutum* , and *Hypericum woodlands* with bushy understories of *Rosa abyssinica* and distinct species of *Solanum* (*S. anguivi and S. nigrum*), and c) *Juniperus procera, Rappanea simensis, and Eucalyptus globulus m*ixed forest in the areas west of Goba. Photo Yohannes O. Kidane 15-30.03.2011.

The Sanetti Plateau covers areas that start at above 3400m asl, the alpine treeline, to the summits. The slopes are covered with lower-statured heather that gives away to Afroalpine vegetation. Here, *Erica* is kept in a shrubby state up to around 4200m asl through repeated burning, freezing temperature, rodent disturbance, and grazing (Miehe and Miehe 1994; Gizaw et al. 2013; Kidane et al. 2022).

The plants are composed of low-statured, perennial life forms e.g., low-stature woody shrubs, herbaceous forbs, graminoids, and cushions with the relative abundance of each related to their location within the massif and local microclimate. Plants like *Dipsacus pinnatifidus* Steud. ex A. Rich.*, Helichrysum splendens* Sims*, Helichrysum citrispinum* Delile.*, Helichrysum cymosum* (L.) D. DON., *Geranium kilimandscharicum* Engl.*,* and *Polygonum afromontanum* Greenway. are common. Other significant plant communities such as Tussock grass like Pentaschistis minor (Ballard & Hubbard) Ballard & Hubbard and *Festuca abyssinica* Hochst. uniquely adopted rosette plants such as *Lobelia* (*L. scebelii* and *L. giberroa*) and *Scenecio spp*. are common.

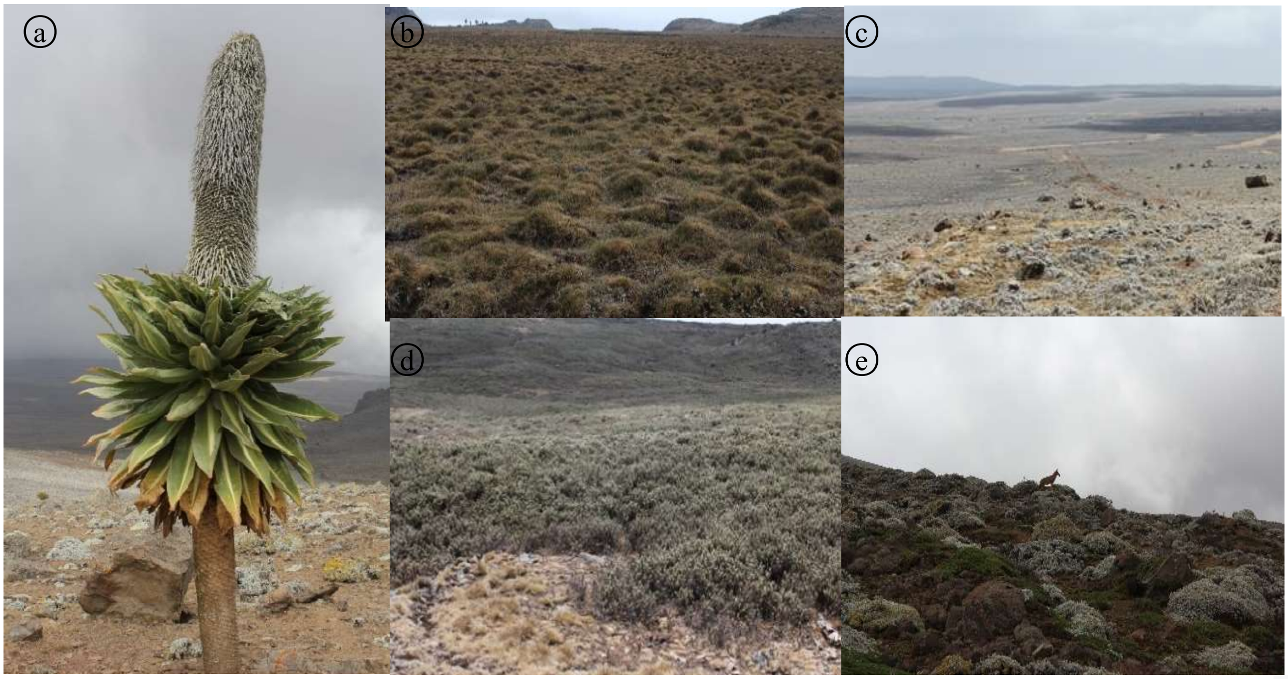


Figure 7: Some of the Afroalpine flagship plants and the Sanetti plateau: a) giant *Lobelia (Lobelia giberroa*); b) Grass species around the Afroalpine lake with signs of solifluction polygons on fine-textured wet soil; c and d) Different species of *Helichrysum (H. splendens, H. citrispinum, H. cymosum, H. jormosissimum, H. splendidum)*; and e) *Helichrysum* shrubs, Erica grooves and A Simien wolf (*Canis simensis*) among the rocky hill of the eastern parts of the plateau. Bale Mountains, Sanetti plateau, (c. 4100 m asl). Photo Yohannes O. Kidane 15-30.03.2011.

In the Afroalpine plateau, beside the ascending harsh climate and fire, the plants are enduring frequent disturbance of the large rodent-like big-headed African mole-rat *Tachyoryctes macrocephalus* (Siebert and Ramdhani 2004). Hence, pioneer plants including *Arabidopsis thaliana* (L.) Heynh., *Myosotis keniensis* T.C.E.Fr.*, Erophila verna* (L.) Chevall.*,* and *Thlaspi alliaceum* L. are common. The plateaus rocks are covered with many species of mosses and lichens **(Figure 8)**. Along the Afroalpine lakes and wetlands, plants including *Alchemilla haumannii* Rothm., *Eriocaulon schimperi* Korn ex Ruhland*, and Carex monostachya* A.Rich are visible**.**

Figure 8: Lichen species on a rock boulder on the Afroalpine of Bale Mountains. a-e) orange Lichen and afroapline rock mosses and lichens species, and f) the prominent Afroalpine rodents, giant mole rats *(Tachyoryctes macrocephalus)* burrow entrance. Photo Yohannes O. Kidane 18.03.2011.

Across all aspects of the massif is the Ericaceous Belt that extends between altitudes 3200m to 3600m asl., followed by Isolated Erica shrubs that extend between 3600m to 4100m asl. On the southern, southwestern, and northwestern parts of the massif are forest, thickets, and scrublands of *Erica arborea* L. and *Erica trimera* (Engl.) Beentje communities. On the southern parts are the older *Erica* stands with a dense branched shrub canopy with moss covering the ground. *E. trimera* forms tall trees up to 15m with abundant epiphytes, especially the moss *Antitrichia curtipendula* (Hedw.) Brid, and the lichen *Usnea articulata* (L.) Hoffm.

In the area above 3,600m asl are dispersed *Erica* groves within Afroalpine *Helichrysum* heathland. Frequent bush fires keeping *Erica* in low (up to 3m), shrubby regeneration phases. *E. trimera* is restricted to distinct patches or solitary individual shrubs. In contrast, in the younger re-sprouting *Erica* individuals are separated by a short-cropped lawn of grasses and herbs (Johansson et al. 2012). The treeline ecotone is inhabited with dense localized stands such as *Alchemilla haumannii* Rothm*, Rubus erlangeri* Engl*, Erica arborea* L., *Erica trimera* (Engl.) Beentje*, and Helichrysum citrispinum* Delile form. Among the sprouting Erica forests, other herbaceous genera include Festuca, Hebenstretia, Romulea, Swertia, and Viola.

Upper Montane forests located on the south and southwestern part of the massif extends between the altitudes 3000m asl to 3400m asl. It is dominated by *Pittosporum viridiflorum* Sims, *Myrsine* *melanophloeos* (L.) R.Br., *Discopodium eremanthum* Chiov., and prominent bushes such as *Rosa abyssinica* R.Br. and *Solanum garae* Friis. Dispersed individuals of large trees such as *Hagenia abyssinica* (Bruce) J.F.Gmel., *Hypericum revolutum* Vahl , and *Juniperus procera* Hochst. ex Endl. In between are patches of Bamboo Forest dominated by bamboo *Sinarundinaria alpina* (K.Schum.) C.S.Chao & Renvoize or *Arundinaria alpina* K.Schum.

The massif falls sharply on the southern part. Here, the upper montane forest's upper margins are large *Erica* trees, which reach up to 15m high. The wet montane forests are characterized by massive mosses, lichen covering the branches, the ground covered by wildflowers and grasses. This mid-altitude habitat area is identified with a high diversity of vascular plants species (Kidane et al. 2019).

In the southern below the escarpments is tropical moist forest, Harenna forest, the trees reach heights of 30m and are covered with epiphytes, creepers, and lianas. The dominant trees include *Buddleja polystachya* Fresen*, Ekebergia capensis* Sparrm*, Maytenus addat* (Loes.) Sebsebe*, Nuxia congesta* R.Br. ex Fresen, *Pittosporum viridiflorum* Sims, *Prunus africana* (Hook. f.) Kalm, *and Schefflera volkensii* (Harms) Harms. Dense thickets of rapidly growing edible mountain *blackberry and Rubus steudneri* Schweinf which grow in the wet season.

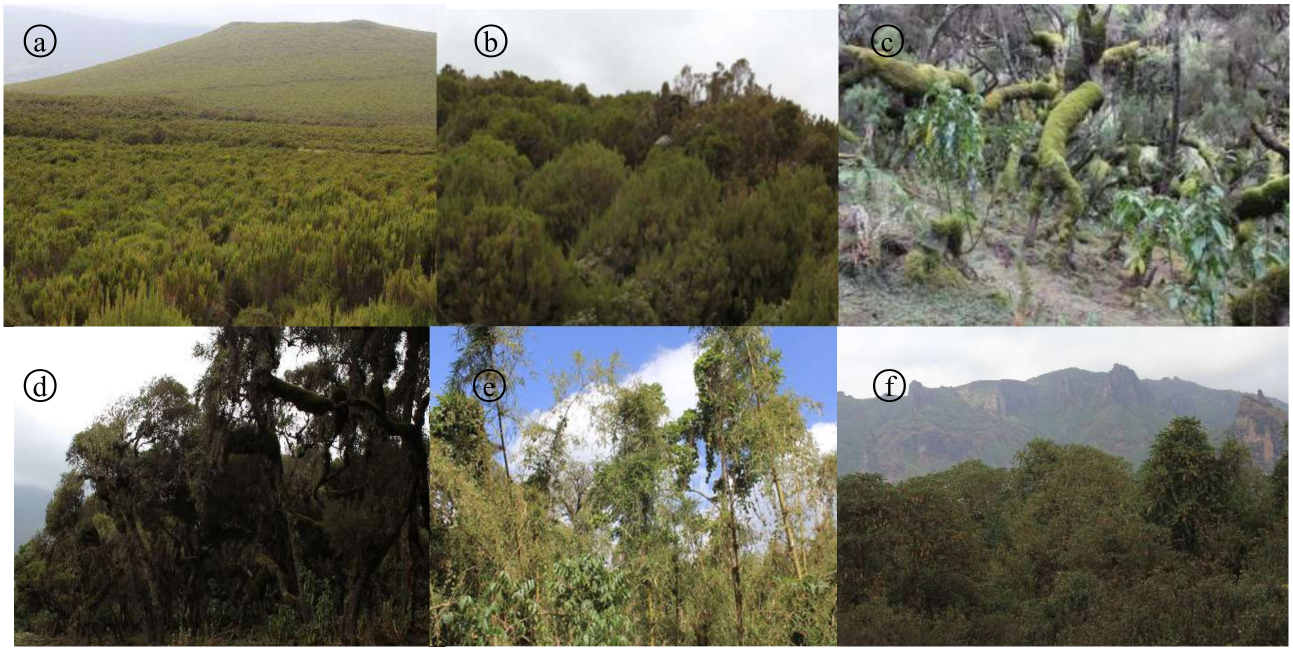


Figure 9: Some the major cover class of the Harenna Escarpments, southern parts of the massif: On the southern slopes, the Harenna escarpment are known for the distinct altitudinal zonation of the Afromontane forests, and the most extensive Ericaceous vegetation on the continent a and b) Erica heathlands, c and d) Older *Erica* stands are with a dense multi-stem shrub canopy with moss covering the ground and the steam, e) the baboo forest and f) a distant look at the escarpment from within the Harenna tropical rainforest. Photo Yohannes O. Kidane 15-30.03.2011.

On the southern borders, there is a growing commercial coffee farmland expansion. Ethiopia is the center of *Coffea arabica* genetic diversity. Within the Herenna forest there are wild cultivar of coffee. Here, aromatic plants such as *Artemisia afra* Jacq. ex Willd. And *Helichrysum splendidum* (Thunb.) Less.

The vegetation below the Harenna forest is typical arid semiarid, thorny savanna with wooded grasslands. Scattered large tree species such as *Balanites aegyptiaca* Del., *Combretum molle* R. Br. ex G. Don *Grewia pubescens* P.Beauv.*, Maerua angolensis* DC.*, Pappea capensis* Eckl. & Zeyh.*, Steganotaenia araliacea* Hochst.*, Terminalia brownii* Fresen., and *Ziziphus mucronata* Willd. are around the town of Dolo-Mena and below. Here onwards dwarf succulent shrubs such as *Caralluma speciosa* N.E.Br.*, Cissus quadrangularis* L.*, Plectranthus puberulentus* J.K.Morton and *Pyrenacantha malvifolia* Engl.*,* and distinct species of *Aloe, Euphorbia* and *Kleinia* are also common.

Fauna

The Bale massif is home to the highest proportion of endemic fauna. The BMNP harbors 28% of Ethiopia's mammalian species (78 of 277), including 55% of its endemics (17 of 31), and 30% of the bird species (278 of 861), including 57% of endemics (16 of 28), as well as many amphibians (Stephens 2001). The Ethiopian flagship endangered animals such as *Canis simensis* (Simien Fox), endangered endemic antelope - *Tragelaphus buxtoni* (Mountain Nyala), *Tragelaphus scriptus meneliki* (Menilek's bushbuck), and *Tachyoryctes macrocephalus* (big-headed African mole rat) (Sillero-Zubiri and Macdonald 1997; Siebert and Ramdhani 2004). On the southern part of the mountains in the Afromontane Forest, there are many larger vulnerable flagship mammals, including *Panthera leo* (lion), *Panthera pardus* (leopard), *Chlorocebus djamdjamensis* (the Bale monkey), and threatened species of primates are common (Mekonnen et al. 2018).

Hydrology

The Sanetti plateau is dissected by rivers and streams that cut deep gorges and create spectacular hydrological systems (Hillman 1986; Hillman 1988). The massive provide water to millions of people, livestock, wildlife, and riparian vegetation in the downstream dry lowlands (Dullo et al. 2015; FZS 2007). This has an important socioeconomic and ecological effect of inundating the riverbanks and supplying lowlands with sediment loaded with nutrients supporting the flourishing of riparian agriculture. The riverbanks support large mammals and avifauna.

The headwaters of the five major rivers (Web, Wabe Shebele, Welmel, Dumal, and Genale) that feed many perennial mountain springs and more than 40 small rivers arise from the Bale Mountains (Hillman 1986;

Dullo et al. 2015). These rivers flow to the south, passing through southern Oromia, Sidama, and farther into Somalia. The Web River formed the extensive underground cavern systems at Sof Omar as it channeled through the limestone foothills (Siebert and Ramdhani 2004).

9.2 Data Collection

The field data collection was carried out in April 2011. Altogether, 448 different plant species of 89 families of 6 functional groups were collected (**Attachment I**). Two floristic inventory transects were established across the elevational gradient along the Goba-Rira-Dolo-Mena Road. The southwestern transect reached from the humid tropical rain forest to the summit at mount Tullu Demtus 4385m asl, with the northeaster transect approach the summit. Starting at 2000m asl nested circular plots of 20 m (1256m^2) and 40 m (5024m^2) radii were established in the Southwestern (19 plots) and Northeaster (13 plots) transect of the massif, and all the way up to the summit at every 250–300m altitude difference. Three replicated plots were established per elevation level following guidelines for optimal sampling along environmental gradients (see Schweiger et al. 2016). All vascular plants in each plot were collected and identified. In addition, the plot's dominant cover type was visually estimated and documented.

We used the same approach across elevational transect. Prior to vegetation sampling, a reconnaissance survey was carried out along the sampling transect to decide potential plot locations. Plot location selection and establishment were carried out randomly after visually judging the area for disturbance, accessibility, and slope. The plots were away from settlements, roads, plantations, farmland, and logging site.

Most species were identified on the spot, yet few critical species were pressed and taken to the National Herbarium of Ethiopia located at Addis Ababa University for further identification. The nomenclature and functional group classification follow published flora of Ethiopia and Eritrea (***All references are given in manuscript #4***). All the recorded vascular plant species were classified as non-endemic (plants that are common all-over east Africa and the rest of the world), Ethiopian endemics (Ethiopia's endemic vascular plant species), and Bale Endemics (restricted to Bale floristic region).

Besides, high resolution spatial and temporally satellite images that go as far back to 50 years, and Digital Elevation Models (DEMs) have been used to analyze the spatio-temporal LULC change dynamics and model climate change impacts on Erica. Landsat images of 30m resolution and Digital Elevation Models (DEM) were downloaded from the United States Geological Survey portal (http://landsat.usgs.gov) at different phases of the research. Besides, high spatial and temporal resolution SPOT (2.5m resolutions) images were also acquired from the SPOT France, through the SPOT planet action funding that was made available to this research. The ground controlling points were collection during the field visit. Each plot's altitude, ground position, and geographic location were recorded using Garmin Global Positioning System (GPS) 3.1.

We used WorldClim's Bioclimatic variable as predictors to model climate change impact on Ericaceous vegetation status and range expansion and retraction (Fick and Hijmans 2017). For this purpose, used Generalized Linear Models (GLMs), Bioclim, Domain, and Support Vector Machines (SVM) modeling algorithms. We also used two representative concentration pathways (RCPs) of the Intergovernmental Panel Climate Change five (IPCC5) climate projections, namely RCP4.5 and RCP8.5, for future climate projection.

10. Results Synopsis

This thesis is composed of four original contributions, which are presented in chapters 1 to 4. The status of the manuscripts, the journals they published at, authors contributions, and other specific journal information are given on the "***List of Manuscripts and Specification of Own Contribution.***" The synopsis of each research article and main findings are discussed below.

Chapter 1 *(Manuscript #1)*

The manuscript focuses on LULC change as a key driver of biodiversity change at a local level and its role in shaping trends of biodiversity, ecosystems, and nature's services to human wellbeing. Such systematic analysis of local-scale land-use change studies, conducted over a range of timescales, helps to uncover the main causes, formulate general principles that explain, predict and suggest remedies to the new land-use changes. We applied satellite imagery to assess spatiotemporal LULC change in the Bale Mountains for four decades. This study aims to identify the main LULC change-related drivers of change in vegetation patterns and to discuss the implications of LULC change on spatial arrangements and trajectories of the vascular plants' diversity and distribution. A better understanding of the degree of impact of each socioeconomic cause will contribute to informed decision-making and management of natural ecosystems, mitigate some unnecessary practices, and increase nature's contributions to human wellbeing. Hence, geospatial data obtained from Remote Sensing is helpful to identify hotspots of species loss and biodiversity conservation significance areas across the massif.

Remote Sensing data acquired from Landsat MSS, Landsat ETM +, and SPOT for four-time steps (1973, 1987, 2000, and 2008) were analyzed using 11 LULC classes predefined based on the dominant plant taxa and cover types of the habitat. Our finding revealed that the area has changed from a quite natural to a more cultural landscape. Natural to agricultural land conversion was extensive, among others. Other cover classes such Closed Erica Forest, Isolated Erica shrubs, Afromontane Grasslands, Afroalpine Dwarf Shrubs, and Herbaceous formations reduced considerably. These cover classes converted to agricultural land and other cover classes. Cover classes such as Upper Montane Forest, Afroalpine Grasslands, Afromontane Dwarf Shrubs and Herbaceous formations, and water bodies showed a slight increase in size. Despite simplification and encroachment of commercial farms, the core area of the Afromontane Rainforest (Harenna forest), located south of the Bale Mountains, has remained relatively stable.

In conclusion, this study documented this biodiversity hotspot's rapid and ecosystem-specific change due to intensified human activities. Agricultural and infrastructural expansion, deforestation, fire, and intensive livestock grazing are some of the leading human activities that are causing biodiversity loss, soil degradation, soil carbon and methane release in Afroalpine ecosystems. Specifically, the ecotone between the Afromontane and the Afroalpine area represent a "hotspot of biodiversity loss" today.

Chapter 2 *(Manuscript #2)*

Ericaceous vegetation of the Bale massif, “The Ericaceous Belt,” is a vital component at the transition between broadleaved forests and Afroalpine vegetation. Understanding the role of anthropogenic climate change on the spatially extremely isolated vulnerable Afroalpine ecosystems and succeeding ecosystems of the Afromontane range, especially those forests and shrublands dominated by Ericaceous species. We hypothesize climate change will result in modified suitability of sites i.e., suitable climate (refugia habitat) for Ericaceous vegetation along the Bale Mountains, which can lead to the expansion of Ericaceous vegetation to higher elevation while retracting from lower altitudes. Consequently, the expansion and dominance of Ericaceous vegetation could negatively impact Afroalpine ecosystems.

We integrated four independent but complementary Species Distribution Models (SDMs), and ensemble the modeling algorithms: Generalized Linear Models (GLMs), Bioclim, Domain, and Support Vector Machines (SVM) algorithms. The modeling was based on bioclimatic variables as environmental predictors. After testing for collinearity, we selected ten historical (current) and future bioclimatic variables. We projected the *Ericaceous* vegetation future distribution under two RCPs (RCP4.5) with average temperature increases 1.4ºC (0.9 to 2.0) and RCP8.5 (2070s) with an average temperature increase of 3.7ºC (2.6 to 4.8). It produces on *Erica* current and future distribution.

Our models and model ensembles produced a robust assessment of climate change impacts and projected areas of potential suitable climate space for *Erica* at 1 km resolution and provided the potential future distribution range of Erica within the massif. Both future projections result in an increase of the Ericaceous vegetation towards the midaltitude of northwestern, northern parts of the massif, and the Sanetti plateau. Overall, close Ericaceous vegetation stands at high altitudes are projected to increase while receding from the lower range of the current distribution range across the massif. The Ericaceous vegetation will persist as one of the massif's critical ecosystems even under changing climate. Moreover, the current Ericaceous vegetation distribution is positively related to the temperature and precipitation trends, which reaffirms the critical role of temperature in shaping species distributions along elevational gradients.

Chapter 3 *(Manuscript #3)*

The Bale Mountains of Ethiopia are home to the largest tropical alpine plateau, with no spacious high summits that provide refugia habitat for upward shift. Plant species geographic ranges shift occurs due to population expansion at the leading edge of their distribution and retraction, adapting, or extinction at the trailing edge. Here, we studied plant species diversity and distribution patterns along elevational gradients and tested potential future impacts of climate change induced warming on those patterns, using species distribution data acquired from nested circular plots along an elevational gradient ranging from 2000 m asl to the highest elevation (4385m asl). Species richness showed a significant mid-elevation richness, hump-shaped species richness patterns on both aspects. It peaks at around 2800m asl on the wet monsoon exposed southwestern escarpment, and at 3500m asl on the dry north-eastern, highly disturbed, with shorter gradient (sampling started at around 2800m asl) and eastern transect. After reaching a peak at mid-altitude, overall richness decreases slowly towards the summit. The proportion of endemic species increases monotonically towards the summit on all slopes and peaks at higher elevations for both transects. The percentage of national endemics showed a significant increase with elevation for both transects. However, the percentage of Bale endemics shows an increase for the Northeaster transect, while it peaked at around 3500m asl for the southwestern transect.

In addition, we modeled the future distribution range of 448 plant species based on their current occurrence records and applying a lapse rate of 0.6ºC per 100m of elevation. Out of the total identified vascular plant species, 114 are endemic to Ethiopia, of which 27 are specific to the Bale Mountain. Using the same data and literature, we project future climate impact on species richness and diversity for three warming scenarios (+ 2ºC, + 3ºC, and + 4ºC). We find that future climate change would significantly alter species distribution patterns with a pronounced impact on the unique ecosystems and Afroalpine endemic species. The analysis of upper lower range of occurrence data of 114 endemics estimated altitudinal range shifts following temperature increase cause the potential local extinction of 8.7%of all endemic species at 2 °C increase. Plants that are threatened with extinction include *Sedum mooneyi* M.G.Gilbert, *Anthemis tigrensis* J.Gay ex A.Rich., *Helichrysum harennensis* Mesfin, *Lobelia rhynchopetalum* (Hochst. ex A.Rich.) Hemsl., *Minuartia filifolia (Forssk.)*, *Senecio schimperi*, *Geranium arabicum* Forssk, *Carex simensis* Hochst. ex A.Rich, *Helichrysum horridum Sch.Bip*, and *Senecio inornatus* DC., three or one in five, are exclusively Bale mountains area endemic. The temperature increases by 3 °C or 4 °C predicted the same rate of endemic extinction, about 36% (of 41 endemic species) local extinction of species.

Chapter 4 (Manuscript #4)

Tropical Africa high mountain ecosystems, particularly Afroalpine ecosystems, own unique environmental conditions that make them high sensitivity to environmental change mainly due to the complex topography-driven isolation resulting in narrow climatic gradients and fragmentation. Contemporarily, the unique ecosystems are exposed to the impacts of multiple drivers of terrestrial ecosystems change mainly to that of Land Use Land Cover (LULC) change, climate change, nitrogen deposition, biotic exchange, and elevated carbon dioxide (CO_2) concentration. This study review provides the contributions of the Ph.D. dissertation (Kidane 2022), which contributes to the advancement of the knowledge on the severity of the synergistic impacts of climate and LULC change on Afroalpine ecosystems and the successful protection of the Afroalpine biodiversity of the Bale massif. The research used *in-situ* plot data and *ex-situ* open data sources, state-of-the-art research approaches, and methodologies. It delivers some missing scientific information on climate and LULC change impacts on the massif's ecosystems and recommends conservation management solutions.

The dissertation presented results from studies that focus on the past forty years of LULC dynamics of the area that quantify the status of the eleven major landcover classes of the massive, modeled climate change impact on the dominant cover classes of the massif, such as ericaceous vegetation. Finally, it presents a study examining how climate change impacts vascular plant diversity and richness patterns. Overall, the studies included in the dissertation developed innovative research approaches and applied cost-effective and efficient biodiversity monitoring approaches that utilize the vast geospatial data acquired from remote sensing and advanced geospatial analysis tools and techniques. Moreover, the manuscripts use open-source software, and the studies are published in open access journals. The modeling and other empirical evidence signaled the area is under the synergistic impact of LULC and climate change, especially the Afroalpine and subalpine ecosystems. Our finding revealed that the once pristine ecosystems have changed from an entirely natural to a more cultural landscape. Unless serious conservation action is taken, these unique ecosystems will be history before long.

11. Conclusion and Recommendation

Ethiopia's biodiversity has been persistently depleted and currently is under imminent danger. Population growth driven demand for natural resources together with natural resources protection and conservation policy failure, top-down political pressure, and lack of ownership and citizens' stewardship are some of the leading causes. The rural poor such as subsistence farmers, indigenous communities and traditional societies have little influence on local to national biodiversity conservation and management planning. Therefore, for effective and efficient biodiversity conservation management awareness-raising, and inclusive bottom-up decision-making practices are imperative. Effective conservation management strategies and planning need to include local people and their traditional acknowledge and sustainable traditional livelihoods and socio-economic situation. The local people's input on the whys of conservation management planning is necessary because they are the ones who are connected to nature and who solely depend on ecosystem services, and among the first to face the most severe and immediate risks of biodiversity loss.

Afromontane ecosystems, particularly the Afroalpine ecosystems at the top are very fragile. The protection and conservation and management of the Afroalpine ecosystem in the face of a fast-changing world is imperative, especially when taking into consideration the recent synergy between climate and LULC change. Conservation management strategies need to address the novel challenges posed by the synergy of climate and LULC change within the areas of the BMNP and within surrounding buffer zone and subzones surrounding the national park.

The likely doubling of Africa's population by 2050, coupled with rapid urbanization, will place tremendous pressure on the continent's biodiversity and human wellbeing. Ethiopia with its current trajectory is not an exception. Hence, diversification of natural resources management approaches, introduction of monitoring technologies, and participatory decision-making will be critical to maintaining biodiversity and ensuring ecological resilience in Afromontane regions.

The available geospatial information from Earth observation combined with *in-situ* data is important to assess the inaccessible and remote Ethiopian Afromontane ecosystems. The four-decade-long LULC change assessment using information from Remote Sensing proves to be a practical approach. The analysis identified the current serious loss and decline of biodiversity in the Bale massif. Further investigation into the causes of the observed loss indicated it is mainly anthropogenic in origin. The loss of biodiversity will reduce ecosystem services and undermine human well-being. Ethiopia's unchecked population growth-driven resources need coupled with the recent economic growth increase the demand for land (agriculture, settlement, and infrastructure), resulting in biodiversity loss and unusual conversion of the natural landscape. Unregulated agricultural land and infrastructural expansion, land grabbing, deforestation (land clearing for agriculture, fuelwood, and charcoal production), and fire are the leading causes of biodiversity loss.

The pristine mountain ecosystems are experiencing a change in plant species and functional group composition, diversity, and distribution and are permanently altered. In the face of the synergy of climate and LULC change across mountain ecosystems will experience even more serious biodiversity loss. Historically, grazing was seasonal and occurred during the wetter months, from April to August, it is currently occurring year-round. The intensified grazing driven by a larger number of domestic animals, large-scale land grabbing, and agricultural expansion are realities that need to be studied and addressed. The Bale pastoralists manage livestock under the godantu system, a vertical transhumance system involving seasonal journeys to the plateau from the surrounding lowlands to graze animals in the Afromontane and Afroalpine vegetation and water from the Afroalpine lakes and access salt from the Afroalpine soils. There is a need to study and sustainably keep the traditional systems. Conservation and adaptation measures are required to expand Bale Mountain National Park (BMNP) territory and create a buffer zone, limit human activities, and access to the Afroalpine region. Plans that ensure pastoral access and sustainable use of the Afroalpine grasslands and heathlands. Agriculture should be restricted to areas outside the park. Even in areas outside the park there are patches of seminatural habitat, especially close to towns. These areas need to be included in biodiversity conservation.

I believe my findings will contribute to the science and understanding of the potential synergistic impacts of climate and LULC change on the biodiversity of the massif. My research that incorporates both *in-situ* (plot data, ground controlling points, and in person investigation) and *ex-situ* gray literature data and geospatial information from Remote Sensing, and geospatial analysis tools and modelling approaches shows such rich resources could improve and support conservation efforts and identify management priorities areas.

To date, the synergistic impacts of climate and LULC change on biodiversity, especially the Afroalpine endemics and the ecosystems services of the Bale Mountains, are not well studied. Further ecological and biogeographic studies and model predictions that consider anthropogenic impacts, ecosystem functioning, and services on the complex interactions between human, biota, and synergistic impacts of climate and LULC change are necessary for a unique sky island system. Furthermore:

- ✓ there is a need for biodiversity management strategies such as monitoring and periodic assessments of ecosystems status. The speed of the ongoing processes clearly shows a need for immediate action if the unique biodiversity of the Bale Mountains is going to be salvaged.
- ✓ There is a need for establishing long-term biodiversity research and monitoring stations that focus on studies carried out by several scientists working together in a multidisciplinary team, especially about the synergistic impacts of climate and LULC change on the functioning of high Afromontane and Afroalpine biota.
- ✓ Reduce anthropogenic stresses and disturbances (fragmentation, deforestation, land clearing for agriculture, etc.) that will hinder species or ecosystem ability to withstand climatic events.
- ✓ Keeping traditional land use in the areas away from the park and the buffer zone to preserve species diversity and salvage sensitive ecosystems.
- ✓ Model and identify refugia that are less affected by climate change, sources for recovery, destinations of climate sensitive migrants, and maximize populations of rare and threatened species.
- ✓ Despite the wide recognition of the area as the world’s most significant biodiversity hotspots, the commitment from the international community, conservation management support, and effective protection seem delayed.
- ✓ There is a need to develop a national mountain definition of a mosaic mountain that fits into the global mountain definition is needed.
- ✓ The introduction of exotic plant species such as *Eucalyptus* and *Cupressus* along the main road, villages, and towns is an immerging threat to biodiversity.

12. Appendix

12.1 Appendix I:

The Bale mountains species list with growth form, IUCN red list status, distribution and endemism, and upper and lower distribution range.

12.2 Appendix II:

Supplementary materials for the research paper: Ericaceous vegetation of the Bale Mountains of Ethiopia will prevail in the face of climate change.

13. References

Aerts, R., Van Overtveld, K., November, E., Wassie, A., Abiyu, A., Demissew, S., Daye, D.D., Giday K., Haile M., et al. (2016). Conservation of the Ethiopian church forests: threats, opportunities, and implications for their management. *Science of the Total Environment*, 551-552, 404-414. doi: 10.1016/j.scitotenv.2016.02.034

African Union Border Programme (AUBP). (2013). Delimitation and Demarcation of Boundaries in Africa: General Issues and Case Studies. Commission of the African Union, Department of Peace and Security, Addis Ababa, Ethiopia.

Allan, N.J.R. (1992). Mountain environments: an assessment. *GeoJournal*, 27, 5-11.

Amente, G. (2005). Rehabilitation and sustainable use of degraded community forests in the Bale mountains of Ethiopia. Inaugural Dissertation. Faculty of Forest and Environmental Sciences, Albert-Ludwigs-University, Freiburg im Breisgau, Germany.

Amsalu, A., and de Graaff, J. (2006). Farmers views of soil erosion problems and their conservation knowledge at Beressa watershed, central highlands of Ethiopia. *Agriculture and Human Values*, 23, 99 - 108.

Antonelli, A., Kissling, W.D., Flantua, S.G.A., Bermúdez, M.A., Mulch, A. et al. (2018). Geological and climatic influences on mountain biodiversity. *Nature Geoscience*, 11, 718–725.

Assefa, Y., Wesche, K., and Fetene, M. (2011). The Status of the Ericaceous Vegetation on the Southern Slope of the Bale Mountains. In Randall, D., Thirgood, S., and Kinahan, A. (eds). (2011). Walia-Special Edition on the Bale Mountains. *Walia: Journal of the Ethiopian wildlife and natural history society*, 158-170.

Barry, R.G., and Seimon, A. (2000). Research for mountain area development: Climatic fluctuations in the mountains of the Americas and their significance. *Ambio*, 29, 364-370.

Barthlott, W., Lauer, W. & Placke, A. (1996). Global distribution of species diversity in vascular plants: Towards a world map of phytodiversity. Erdkunde, 50, 317-328.

Barthlott, W., Hostert, A., Kier, G., Küper, W., Kreft, H., Mutke, j., Rafiqpoor, J.M., and Sommer, J. H. 2007. Geographic patterns of vascular plant diversity at continental to global scales. Erdkunde 61(4), 305-315.

Beck, E., Rehder, H., and Kokwaro, J.O. (1990). Classification and mapping of the vegetation of the alpine zone of Mount Kenya (Kenya). Geographical Bernensis African Studies Series A8. Mt. Kenya Area, 41- 46.

Beierkuhnlein, C. (2002a). Landscape prognosis: future landscapes. In: Bastian, O., and Steinhardt, U. (eds.): Development and perspectives of landscape ecology. Kluwer, Dordrecht, Boston, London, pp. 195-203.

Beierkuhnlein, C. (2002b). Nature conservation. In: Bastian, O., and Steinhardt, U. (eds.): Development and Perspectives of Landscape Ecology. Kluwer, Dordrecht, Boston, London. pp. 373-385.

Beierkuhnlein, C. (2007). Biogeografie. Die räumliche Organisation des Lebens in einer sich verändernden Welt. Eugen Ulmer Verlag, Stuttgart, Germany. 400 pp.

Beierkuhnlein, C., and Jentsch, A. (2005). Ecological importance of species diversity. A review on the ecological implications of species diversity in plant communities *in* Henry, R. (ed.): Plant Diversity and Evolution: Genotypic and Phenotypic Variation in Higher Plants, CAB International, Wallingford, 249-285.

Bhattarai, K.R., and Vetaas, O.R. (2003). Variation in plant species richness of different life forms along a subtropical elevation gradient in the Himalayas, east Nepal. *Global Ecology and Biogeography*, 12(4), 327 – 340.

Bonnefille, R. (1983). Evidence for a cooler and drier climate in the Ethiopian uplands towards 2.5 Mys ago. *Nature,* 303, 487-491. doi.org/10.1038/303487a0

Breckle, S.W. (2002). Walter's Vegetation of the Earth: The Ecological Systems of the Geo-Biosphere. 4th ed. Completely Revised and Enlarged Edition. Translated from the 7th, Completely Revised and Enlarged German Edition by Gudrun and David Lawlor. Springer-Verlag. Berlin, Heidelberg. Germany. 527p.

Brigham, A.P. (1919). Principles in the determination of boundaries. *Geographical Review*, 7 (4), 201-219.

Brochmann, C., Gizaw, A., Chala, D., Kandziora, M., Eilu, G., Popp, M., Pirie, M.D., and Gehrke, B. (2021). History and evolution of the Afroalpine flora: in the footsteps of Olov Hedberg. *Alpine Botany,* (2021), 1-23. doi.org/10.1007/s00035-021-00256-9

Burgess, N., Hales, J.D., Underwood, E., Dinerstein, E., Olson, D., Itoua, I., Schipper, J., Ricketts, T., and Newman, K. (2004). Terrestrial Ecoregions of Africa and Madagascar: A Conservation Assessment. WWF. USA. Island Press. Washington. 518p.

Burgess, N.D., Balmford, A., Cordeiro, N.J., Fjeldsa, J., Kuper, W., Rahbek, C., et al. (2007). Correlations among species distributions, human density, and human infrastructure across the high biodiversity tropical mountains of Africa. *Biological Conservation*, 134(2), 164-177. doi.org/10.1016/j.biocon. 2006.08.024**.**

Bussmann, R.W. (2006). Vegetation zonation and nomenclature of African mountains: An Overview. *Lyonia*, 11, 41-66.

Buytaert, W., Cuesta-camacho, F. & Tobon, C. (2011). Potential impacts of climate change on the environmental services of humid tropical alpine regions. *Global Ecology and Biogeography*, 20, 19 - 33. https://doi.org/10.1111/j.1466-8238.2010.00585.x

Campbell, J.B., and Wynne, R.H. (2011). Introduction to Remote Sensing. Guilford Publications. New York.

Chala, D., Brochmann, C., Psomas, A., Dorothee Ehrich, D., Gizaw, A., Masao, C.A., Bakkestuen, V., Zimmermann, N.E. (2016). Goodbye to tropical alpine plant giants under warmer climates? Loss of range and genetic diversity in *Lobelia rhynchopetalum*. *Ecology and Evolution,* 2016 (6), 8931–8941. doi.org/10.1002/ece3.2603

Chala, D., Niklaus, E., Zimmermann, E.Z., Brochmann, C., and Bakkestuen, V. (2017). Migration corridors for alpine plants among the “sky islands” of eastern Africa: do they, or did they exist? *Alpine Botany*, 127(2), 133-144. doi:10.1007/s00035-017-0184-z

Chan, R.Y., Vuille, M., Hardy, D.R., Bradley, R.S. (2008) Intra seasonal precipitation variability on Kilimanjaro and the East African region and its relationship to the large-scale circulation. *Theoretical and Applied Climatology,* 93, 149-165.

Colwell, R.K., Brehm, G., Cardelús, C.L., Gilman, A.C., and Longino, J.T. (2008). Global warming, elevational range shifts, and lowland biotic attrition in the wet tropics. *Science*, 322, 258–261.

CSA (2009). Federal Democratic Republic of Ethiopia Central Statistical Agency. Agricultural sample survey. Volume I.

Darbyshire, I., Lamb, H., and Umer, M. (2003). Forest clearance and regrowth in northern Ethiopia during the last 3000 years. *The Holocene,* 13, 537-546. doi.org/10.1191/0959683603hl644rp

Dawson, M.N., Axmacher, J.C., Beierkuhnlein, C., Blois, J., Bradley, B.A., Cord, A.F., Dengler, J. et al. (2016). A second horizon scan of biogeography: Golden Ages, Midas touches, and the Red Queen. opinions, perspectives & reviews. Perspective, Frontiers of biogeography. 8.4, e29770, 2016. 1-30.

Davis, S.D., Heywood, V.H., Herrera-MacBryde, O., Villa Lobos, J.L. & Hamilton, A.C. (eds.), 1997. Centres of Plant Diversity. A Guide and Strategy for their Conservation. Vol. 3: The Americas. IUCN Publications Unit, Cambridge.

Davis, M.B., Shaw, R.G., Etterson, J.R. (2005). Evolutionary responses to changing climate. *Ecology,* 86 (7), 1704 - 1714. doi.org/10.1890/03-0788

Diamond, J. (1999). Guns, Germs, and Steel: The Fate of Human Societies. W.W. Norton and Company Inc.NY.

Diaz, S., Fargione, J., Chapin, F.S III., and Tilman, D. (2006). Biodiversity loss threatens human wellbeing. *PLoS Biol,* 4(8), 1300 -1305. doi.org/10.1371/journal.pbio.0040277

Dullo, B.W., Grootjans, A.P., Roelofs, J.G.M., Senbeta, A.F., Fritz, C. (2015). Fen mires with cushion plants in Bale Mountains, Ethiopia. *Mires and Peat*, 15 (2014/15), 1-10.

Earn, D.J.D., Levin, S.A., and Rohani, P. (2000). Coherence and conservation. *Science,* 290, 1360 -1364.

Eckholm, P.E. (1975). The deterioration of mountain environments. *Science*, 189, 764 - 770.

Enquist, C.A.F. (2002). Predicted regional impacts of climate change on the geographical distribution and diversity of tropical forests in Costa Rica. *Journal of Biogeography*, 29(4), 519 – 534. doi: 10.1046/j. 1365-2699.2002.00695.x

Fick, S.E. and Hijmans, R.J. (2017). WorldClim 2: new 1km spatial resolution climate surfaces for global land areas. *International Journal of Climatology,* 37 (12), 4302-4315.

Flantua, S.G.A., Payne, D., Borregaard, M.K., Beierkuhnlein, C., Steinbauer, M.J., Dullinge, S., Ess, F., Irl, S.D.H., Kienle, D., et al. (2020). Snapshot isolation and isolation history challenge the analogy between mountains and islands used to understand endemism. *Global Ecology Biogeography,* 2020 (29), 1651–1673. doi:10.1111/geb.13155

Frankfurt Zoological Society (FZS). (2007). Bale Mountains National Park General Management Plan (MBNP-GMP) 2007-2017. Frankfurt. Germany. http://zgf.de. Accessed on December 15th, 2009. 238p.

Friis, I. (1992) Forests and forest trees of northeast tropical Africa. Their natural habitats and distribution patterns in Ethiopia, Djibouti, and Somalia. Kew Bull Additional Series 15, HMSO, London. 396p.

Friis, I., Thulin, M., Adsersen, H. and Burger, A.-M. (2005). Patterns of plant diversity and endemism in the Horn of Africa. *Biologiske Skrifter,* 55, 289-314. ISSN 0366-3612. ISBN 87-7304-304-4.

Funnell, D.C., and Price, M.F. (2003). Mountain geography: a review. *Geographical Journal,* 169(3), 183 – 190. doi: 10.1111/1475-4959.00083

Gamachu, D. (1990). Some patterns of Altitudinal variation of climatic elements in the mountainous regions of Ethiopia. In Messerli B and Hurni H (eds.). African Mountains and Highlands: Problems and Perspectives. The African Mountain Association (AMA). Walsworth Press Co., Inc., Missouri.

Gebreegziabher, T. (1988). Vegetation and environment of the Mountains of Ethiopia: Implications for utilization and conservation. *Mountain Research and Development*, 8, 211-216.

Gebreegziabher, T. (1990). Vegetation and environment of the mountains of Ethiopia: Implications for utilization and conservation. In Messerli B and Hurni H (eds.). African Mountains and Highlands: Problems and Perspectives. The African Mountain Association (AMA). Walsworth Press Co., Inc., Missouri.

Gebreegziabher, T. (1991). Management of mountain environments and genetic erosion in Tropical Mountain systems: The Ethiopian Example. *Mountain Research and Development*, 11, 225-230.

Gehrke, B., and Linder, H.P. (2009). The scramble for Africa: pan-temperate elements on the African high mountains. Proceedings of the Royal Society B: *Biological Sciences*, 276(1667), 2657-2665. doi:10.1098/rspb.2009.0334

Gehrke, B., Linder, H.P. (2014). Species richness, endemism, and species composition in the tropical Afroalpine flora. *Alpine Botany*, 2014(124), 165-177. doi 10.1007/s00035-014-0132-0

Gerrard, J. (1990). Mountain environments: an examination of the physical geography of mountains. Belhaven Press, London, 317p.

Getahun, A. (1984). Stability and instability of mountain ecosystems in Ethiopia. *Mountain Research and Development*, 4, 39 - 44. doi.org/10.2307/3673167

Gil-Romera, G., Adolf, C., Benito, B.M., Bittner, L., Johansson, M.U., Grady, D.A., Lamb, H.F., Lemma, B., Fekadu, M., et al. (2019). Long-term fire resilience of the Ericaceous Belt, Bale Mountains, Ethiopia. *Biology Letters,* 15(7), 1-5. doi:10.1098/rsbl.2019.0357

Gizaw, A., Brochmann, C., Nemomissa, S., Wondimu, T., Masao, C.A., Tusiime, F.M., et al. (2016). Colonization and diversification in the African 'sky islands': insights from fossil-calibrated molecular dating of Lychnis (Caryophyllaceae). *New Phytologist,* 211(2), 719-734. doi: 10.1111/nph.13937.

Gizaw, A., Kebede, M., Nemomissa, S., Ehrich, D., Bekele, B., et al. (2013). Phylogeography of the heathers Erica arborea and E. trimera in the afro-alpine 'sky islands' inferred from AFLPs and plastid DNA sequences. *Flora - Morphology Distribution Functional Ecology of Plants*, 208(7), 453-463. doi: 10.1016/j.flora.2013.07.007

Gonzalez-Trueba, J.J., and Garcia-Ruiz, J.M. (2012). Jack D. Ives and the geoecology of mountain areas. *Pirineos*, 167, 7-13. doi:10.3989/Pirineos.2012.167001

Grabherr, G., Gottfried, M., and Pauli, H. (2000). GLORIA: A Global Observation Research Initiative in Alpine Environments. *Mountain Research and Development*, 20(2), 190-191. doi: 10.1659/0276-4741(2000)020[0190:GAGORI]2.0.CO;2

Grepperud, S. (1996). Population Pressure and Land Degradation: The Case of Ethiopia. *Journal of Environmental Economics and Management*, 30, 18-33. doi.org/10.1006/jeem.1996.0002

Grosjean, M., and Messerli, B. (1990). African mountains and highlands: Potential and constraints. In Messerli B and Hurni H (eds.). African Mountains and Highlands: Problems and Perspectives. The African Mountain Association (AMA). Walsworth Press Co., Inc., Missouri.

Grytnes, J.A. (2003a). Ecological interpretations of the mid-domain effect. *Ecology Letters,* 6, 883–888. doi: 10.1046/j.1461-0248.2003. 00511.x

Grytnes, J.A. (2003b). Species-richness patterns of vascular plants along seven altitudinal transects in Norway. *Ecography*, 26(3), 291-300. doi.org/10.1034/j.1600-0587.2003.03358.x

Guta, D.D. (2012). Assessment of Biomass Fuel Resource Potential and Utilization in Ethiopia: Sourcing Strategies for Renewable Energies. *International Journal of Renewable Energy Research,* 2(1), 131-139

Hailu, B.T., Fekadu, M., and Nauss, T. (2018). Availability of global and national scale land cover products and their accuracy in mountainous areas of Ethiopia: a review. *Journal of Applied Remote Sensing*, 12(4), 1-13. doi: 10.1117/1.JRS.12.041502.

Hannah, L., Midgley, G.F., Miller, D. (2002). Climate change-integrated conservation strategies. *Global Ecology and Biogeography*, 11(6), 485-495. doi:10.1046/j.1466-822X.2002.00306.x

Hansen, J., Sato, M., Ruedy, R., Lo, K., Lea, D.W., and Medina-Elizade, M. (2006). Global temperature change. *PNAS*, 103(39), 4288–14293. doi.org/10.1073/pnas.0606291103

Hedberg, O. (1951). Vegetation belts of the East African mountains. Stockholm: *Svenska botaniska fôreningens,* 45(1), 140-202.

Hedberg, O. (1964). Features of Afroalpine Plant Ecology. *Acta Phytogeographica Suecica*, 49, 1-144

Hillman, J.C. (1986). Conservation in Bale Mountains National Park, Ethiopia. *Oryx*, 20(2), 89-94. doi:10.1017/S0030605300026314

Hillman, J.C. (1988). The Bale Mountains National Park Area, Southeast Ethiopia and its Management. *Mountain Research and Development,* 8 (2/3), 253-258.

Hillman, J.C. (1990). The Bale Mountains National Park area, southeastern Ethiopia, and its management. In Messerli B and Hurni H (eds). African Mountains and Highlands: Problems and Perspectives. The African Mountain Association (AMA). Walsworth Press Co., Inc., Missouri.

Hoorn, C., Perrigo, A., and Antonelli, A. eds. (2018). Mountains, Climate and Biodiversity, First Edition. John Wiley & Sons Ltd. 1807, New York, NY. 544p.

Human Development Report (HDR). (2020). The next frontier: Human development and the Anthropocene. United Nations Development Program. UN Plaza, New York, NY 10017. USA.

Hurni, H. (1993). Land degradation, famine, and land resource scenarios in Ethiopia. In: Pimentel, D. (ed.). World Soil Erosion and Conservation. Cambridge, UK: Cambridge University Press.

Hurni, H., Abate, S., Bantider, A., Debele, B., Ludi, E., Portner, B., Yitaferu, B., and Zeleke, G. (2010). Land Degradation and Sustainable Land Management in the Highlands of Ethiopia. Global Change and Sustainable Development. North-South perspective. *Geographica Bernesia*, 5, 187-207. doi:10.13140/2.1.3976.5449

Hurni, H., and Ludi, E. (2000). Reconciling Conservation with Sustainable Development: A Participatory Study Inside and Around the Simien Mountains National Park, Ethiopia. Bern, Switzerland.

Huston, A.M. (1994). Biological Diversity. The Coexistence of Species on Changing Landscapes. Cambridge University press. Athenaeum Press Ltd. Gateshead. 682p.

Ingebretsen, E. (2015). A Thirsty Third World: How Land Grabs Are Leaving Ethiopia in the Dust. wH2O: *The Journal of Gender and Water,* 4 (11), 94-102.

Innes, J.L. and Koch, B. (1998). Forest biodiversity and its assessment by Remote Sensing. *Global Ecology and Biogeography*, 7, 397-419.

IPCC (2014). In: Pachauri, R.K., Meyer, L.A. (Eds.), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team. IPCC, Geneva, Switzerland. 151p.

Itescu, Y. (2018). Are island-like systems biologically similar to islands? A review of the evidence. *Ecography*, 42, 1-17. doi.org/10.1111/ecog.03951.

Itescu, Y. (2019). Are island-like systems biologically similar to islands? A review of the evidence. *Ecography*, 42, 1298–1314. doi: 10.1111/ecog.03951

Jackson, S.T. (2009). Introduction: Humboldt, Ecology, and the Cosmos. In Essay on the Geography of Plants. Alexander Von Humboldt and Aime Bonpland. Edited with an Introduction by Stephen T. Jackson Translated by Sylvie Romanowski. The University of Chicago Press, Chicago. USA. 306p.

Jacobs, M.J., and Schloeder, C.A. (2001). Impacts of conflict on biodiversity and protected areas in Ethiopia Washington, D.C.: Biodiversity Support Program. 45p.

Jensen, J.R. (2015). Introductory Digital Image Processing: A Remote Sensing perspective. Glenview, IL, Pearson Education Inc.558p.

Jentsch, A., and Beierkuhnlein, C. (2003). Global climate change and local disturbance regimes as interacting drivers for shifting altitudinal vegetation patterns. *Erdkunde,* 57, 216-231.

Johansson, M.U., and Granström, A. (2014). Fuel, fire, and cattle in African highlands: traditional management maintains a mosaic heathland landscape. *Journal of Applied Ecology*, 51, 1396-1405. doi: 10.1111/1365-2664.12291

Johansson, M.U., Fetene, M., Malmer, A., and Granstrom, A. (2012). Tending for cattle: traditional fire management in Ethiopian montane heathlands. *Ecology and Society*, 17(3), 1-15. doi.org/10.5751/ES-04881-170319**.**

Jump, A.S., Huang, T.J., and Chou, C.H. (2012). Rapid altitudinal migration of mountain plants in Taiwan and its implications for high altitude biodiversity. *Ecography*, 35, 204 - 210. doi.org/10.1111/j.1600-0587.2011.06984.x.

Jump, A.S., Matyas, C., and Penuelas, J. (2009). The altitude-for-latitude disparity in the range retractions of woody species. *Trends Ecology and Evolution*, 24(12), 694-701. doi.org/10.1016/j.tree. 2009.06.007.

Kapos, V., Rhind, J., Edwards, M., Price, M. F., and Ravilious, C. (2000). Developing a map of the world's mountain forests. In M.F. Price and N. Butt (eds.) (2000) Forests in sustainable mountain development: a state of knowledge report for 2000. CAB International, Wallingford: 4-9.

Karagulle, D., Frye, C., Sayre, R., Breyer, S., Aniello, P., Vaughan, R., Wright, D. (2017). Modeling global Hammond landform regions from 250-m elevation data. *Transactions in GIS*, 21(5), 1040–1060. http://dx.doi.org/10.1111/tgis.12265

Kibert, C.J., Thiele, L., Peterson, A. and Monroe, M. (2010). The ethics of sustainability, in theory and in fact," In reshaping the built environment, Charles J. Kibert, ed., Washington, D.C.: Island Press.

Kidane, Y., Stahlman, R., Beierkuhnlein, C. (2012). Vegetation dynamics, and land use and land cover change in the Bale Mountains, Ethiopia. *Environmental Monitoring Assessment*, 184 (12), 7473-7489. doi.org/10.1007/s10661-011-2514-8.

Kidane, Y.O., Steinbauer, M.J., and Beierkuhnlein, C. (2019). Dead end for endemic plant species? A biodiversity hotspot under pressure. *Global Ecology and Conservation*, 19, 1-12. doi.org/10.1016/j.gecco. 2019.e00670

Körner, C. (2000). Why are there global gradients in species richness? Mountains might hold the answer. *Trends in Ecology and Evolution*, 15, 513–514. doi.org/10.1016/S0169-5347(00)02004-8

Körner, C. (2003). Alpine Plant Life: Functional Plant Ecology of High Mountain Ecosystems, Springer-Verlag, Berlin. Germany. 349p.

Körner, C. (2004). Through enhanced tree dynamics carbon dioxide enrichment may cause tropical forests to lose carbon. *Philosophical Transactions of The Royal Society B Biological Sciences*, 359(1443), 493 - 8. doi.org/10.1098/rstb.2003.1429

Körner, C. (2007). The use of 'altitude' for ecological research. *Trends in Ecology and Evolution*, 22 (11), 569-574. doi.org/10.1016/j.tree.2007.09.006**.**

Körner, C.; Hiltbrunner, E. (2021). Why Is the Alpine Flora Comparatively Robust against Climatic Warming? Diversity: 13, 383. https://doi.org/10.3390/ d13080383

Körner, C., and Spehn, E. (2019). A Humboldtian view of mountains. *Science,* 365 (6458), 1061-1061. doi: 10.1126/science.aaz4161.

Körner, C., Jetz, W., Paulsen, J., Payne, D., Rudmann-Maurer, K., Spehn, E.M. (2017). A global inventory of mountains for bio-geographical applications. *Alpine Botany*, 127, 1-15. doi.org/10.1007/s00035-016-0182-6.

Körner, C., Paulsen, J., and Spehn, E.M. (2011). A definition of mountains and their bioclimatic belts for global comparisons of biodiversity data. *Alpine Botany*, 121, 73-78. doi:10.1007/s00035-011-0094-4

Kreyling, J., Wana, D., Beierkuhnlein, C. (2010). Climate warming and tropical plant species – consequence of potential upslope shift of isotherms in southern Ethiopia. *Diversity and Distribution*, 16, 593 - 605. doi.org/10.1111/j.1472-4642.2010.00675.x.

Kuzmicheval, E.A., Debella, H., Khasanov, B., Krylovich, O., Babenko, A. et al. (2013). Holocene hyrax dung deposits in the Afroalpine belt of the Bale Mountains (Ethiopia) and their palaeoclimatic implication. *Environmental Archaeology*, 18(1), 72 - 81. doi:10.1179/1461410313Z.00000000018

Kuzmicheval, E.A., Khasanov, B.F., Krylovich, O.A., Savinetsky, A.B. (2014). Vegetation and climate reconstruction for the Bale mountains (Ethiopia) in the Holocene according to the pollen analysis and radiocarbon dating of zoogenic deposits. *Doklady Biological Science*, 458, 281-285. doi.org/10.1134/ S0012496614050019.

Lambin, E.F., et al. (2003). Dynamics of land-use and landcover change in tropical regions. *Annual Review of Environment and Resources*, 28, 205–241. doi.org/10.1146/annurev.energy.28.050302.105459

Laurenson, K., Sillero-Zubiri, C., Thompson, H., Shiferaw, F., Thirgood, S., and Malcolm, J. (1998). Disease as a threat to endangered species: Ethiopian wolves, domestic dogs, and canine pathogens. *Animal Conservation*, 1, 273-280.

Lewis, S.L., and Maslin, M.A. (2015). Defining the Anthropocene. Nature, research perspective. 519, 171-180. doi:10.1038/nature14258

Lomolino, M.V. (2001). Elevation gradients in species density: historical and prospective views. *Global Ecology and Biogeography,* 10, 3-13. doi.org/10.1046/j.1466-822x.2001.00229.x.

Lovejoy, T. (2008). Climate change and biodiversity. *Revue scientifique et technique (International Office of Epizootics)*, 27 (2), 331-338.

Lovejoy, T.E. and Hannah, L. (2005). Climate Change and Biodiversity. Yale University Press. NH. USA.

Lulekal, E., Kelbessa, E., Bekele, T., and Yineger, H. (2008). An ethnobotanical study of medicinal plants in Mana Angetu district, Southeastern Ethiopia. *Journal of Ethnobiology and Ethnomedicine*, 4, 1-10. doi.org/10.1186/1746-4269-4-10

Malcolm, J.R., Liu, C., Neilson, R.O., Hansen, A., Hannah, L. (2006) Global warming and extinctions of endemic species from biodiversity hotspots. *Conservation Biology*, 20(2), 538 - 548. doi.org/ 10.1111/j.1523-1739.2006.00364.x.

MEA. (2005). Status and trends in mountain systems. Washington: World Resources Institute.

Mekonnen, A., Fashing, P.J., Bekele, A., Hernandez-Aguilar, R.A., Rueness, E.K., and Stenseth, N.C. (2018). Dietary flexibility of Bale monkeys (Chlorocebus djamdjamensis) in southern Ethiopia: effects of habitat degradation and life in fragments. *BMC Ecology*, 18(1), 1-20. doi: 10.1186/s12898-018-0161-4.

Merckx, V.S.F.T., Hendriks, K.P., Beentjes, K.K., Mennes, C.B., Becking, L.E., Peijnenburg, K.T.C.A., Afendy, A., Arumugam, N., de Boer, et al. (2015). Evolution of endemism on a young tropical mountain. *Nature*, 524, 347 – 350. doi:10.1038/nature14949.

Messerli, B. (2011). Global Change and the World's Mountains Where Are We Coming From, and Where Are We Going To? *Mountain Research and Development*, 32(Supplement Issue), S55–S63. doi.org/10.1659/MRD-JOURNAL-D-11-00118.S1

Messerli, B., and Hurni, H. (eds.). (1990). African Mountains and Highlands: Problems and Perspectives. The African Mountain Association (AMA). Walsworth Press Co., Inc., Missouri.

Messerli, B., and Ives, J.D. (1997). Mountains of the world: a global priority. edited by B. Messerli and J.D. Ives. Parthenon Pub. Group, New York. 495p.

Messerli, B., Hurni, H., Woldesemait, B., Tedla, S., Ives, J.D., and Woldemariam, M. (1990). African mountains and Highlands: An introduction. In Messerli, B., and Hurni, H. (eds.). African Mountains and Highlands: Problems and Perspectives. The African Mountain Association (AMA). Walsworth Press Co., Inc., Missouri.

Meybeck, M., Green, P., and Vörösmarty, C.J. (2001). A new typology for mountains and other relief classes: An application to global continental water resources and population distribution. *Mountain Research and Development,* 21(1), 34-45.

Miehe, G., and Miehe, S. (1994). Ericaceous Forests and Heathlands in the Bale Mountains of South Ethiopia: Ecology and Man's Impact. Stiftung Waldurhaulting in Afrika. Humburg,Germany. 206 p.

Mittermeier, R.A., Robles Gil, P., Hoffmann, M., Pilgrim, J., Brooks, T., Mittermeier, C.G., Lamoreux, J., da Fonseca, G.A.B. (2004). Hotspots Revisited: Earth's Biologically Richest and Most Endangered Terrestrial Ecoregions. CEMEX, Mexico City. Mexico.

Monasterio, M., and Vuilleumier, F. (1986). Introduction: High tropical Mountain Biota of the World. In High Mountains Tropical Biogeography. Eds. Vuilleumier, F. and Monasterio, M. Published by Oxford University Press and the American Museum of Natural History. Oxford University Press. NY. U.S.A.

Mutke, J., and Barthlott, W. (2005). Patterns of vascular plant diversity at continental to global scales. *Biologiske Skrifter*, 55, 521–531. ISSN 0366-3612. ISBN 87-7304-304-4.

Mutke, J., Kier, G., Braun, G., Schultz, Chr, Barthlott, W. (2001). Patterns of African vascular plant diversity: a GIS based analysis. *Systematics and Geography of Plants*, 71, 1125-1136. doi: 10.2307/3668744

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B. & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, 403, 853-858. doi.org/10.1038/35002501

Nagy, L., Grabherr, G. (2009) The Biology of Alpine Habitats. Oxford University Press, Oxford. 376p.

National Biodiversity Strategy and Action Plan (NBSAP) (2005). Democratic Republic of Ethiopia. Institute of Biodiversity Conservation. Addis Ababa. Ethiopia. http://www.cbd.int/doc/world/et/et-nbsap-01-en.pdf. Accessed on Sep. 20th, 2009.

Navalgund, R.R., Jayaraman, V., and Roy, P.S. (2007). Remote Sensing applications: An overview. *Current Science*, 93, 1747-1766.

Nogués-Bravo, D., López-Moreno, J.I., and Vicente-Serrano, S. M. (2012). Climate Change and its Impact. Mediterranean Mountain Environments. *Mediterranean Mountain Environments,* 185-201. doi: 10.1002/9781119941156.ch9

Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., et al. (2001). Terrestrial Ecoregions of the World: A New Map of Life on Earth. *BioScience,* 51(11), 933 - 938. doi.org/10.1641/0006-3568(2001)051[0933:TEOTWA]2.0.CO;2

Olson, J. M., Alagarswamy, G., Andresen, J. A., Campbell, D. J., Davis, A. Y., et al. (2008). Integrating diverse methods to understand climate–land interactions in East Africa. *Geoforum*, 39(2), doi:10.1016/j.geoforum.2007.03.011.

Orlowska, I., and Klepeis. P. (2018). Ethiopian church forests: a socio-religious conservation model under change. *Journal of Eastern African Studies* 12(4): 674-695. doi:10.1080/17531055.2018.1519659

Osmaston, H.A., Mitchell, W.A., Osmaston, J.A.N. (2005). Quaternary glaciation of the Bale mountains, Ethiopia. *Journal of Quaternary Science*, 20(6), 593 – 606. doi:10.1002/jqs.931

Ossendorf, G., Groos, A.R., Bromm, T., Tekelemariam, M.G., Glaser, B., Lesur, J., et al. (2019). Middle Stone Age foragers resided in high elevations of the glaciated Bale Mountains, Ethiopia. *Science*, 365(6453), 583–587. doi: 10.1126/science.aaw8942.

Parmesan, C. (2006). Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics,* 37, 637-669. doi.org/10.1146/annurev.ecolsys. 37.091305. 110100.

Peters, G. P. et al. (2012). Rapid growth in CO_2 emissions after the 2008_2009 global financial crisis. *Nature Climate Change,* 2, 2-4.

Pettorelli, N., Laurance, W.F., O'Brien, T.G., Wegmann, M., Nagendra, H., and Turner, W. (2014). Satellite Remote Sensing for applied ecologists: opportunities and challenges. *Journal of Applied Ecology*, 51, 839-848. doi: 10.1111/1365-2664.12261

Pihl, E., Martin, M.A., Blome, T., Hebden, S., Jarzebski, M.P., Lambino, R.A., et al. (2019). 10 New Insights in Climate Science. Future Earth & The Earth League, Stockholm. 34p.

QGIS Development Team (2018). QGIS Geographic Information System. Open-Source Geospatial Foundation Project. http://qgis.osgeo.org.

R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing [Internet]. http://www.R-project.org/.

Rahbek, C. (2005). The role of spatial scale and the perception of large-scale species-richness patterns. *Ecology Letters*, 8 (2), 224-239. doi.org/10.1111/j.1461-0248.2004.00701.x.R.

Rahbek, C., Borregaard, M.K., Antonelli, A., Colwell, R.K., Holt, B.G., Nogues-Bravo, D., et al. (2019a) Building Mountain biodiversity: Geological and evolutionary processes. *Science*, 365 (6458), 1114-1119. doi: 10.1126/science.aax0151.

Rahbek, C., Borregaard, M.K., Colwell, R.K., Dalsgaard, B., Holt, B.G., et al. (2019b). Humboldt's enigma: What causes global patterns of mountain biodiversity? *Science*, 365 (6458), 1108-1113. doi: 10.1126/science.aax0149

Rahbek, C., Borregaard, M.K., Hermansen, B., Nogues-Bravo, D., and J. Fjeldså. (2019c). Center for Macroecology, Evolution and Climate. https://macroecology.ku.dk/resources/mountain_regions (accessed on June 01, 2021).

Razgour, O., Kasso, M., Santos, H., and Juste, J. (2020). Up in the air: Threats to Afromontane biodiversity from climate change and habitat loss revealed by genetic monitoring of the Ethiopian Highlands bat. *Evolutionary Application*, 2021 (14), 794-806. doi.org/10.1111/eva.13161.

Richter, M. (2008). Tropical Mountain forests distribution and general features. In Gradstein, S.R., Homeier, J., and Gansert, D., (eds.). The Tropical Mountain Forest Patterns and Processes in a Biodiversity Hotspot. Göttingen Centre for Biodiversity and Ecology. *Biodiversity and Ecology Series*, 2, 7-24. 224p.

Ring, U. (2014). The East African Rift System. *Austrian Journal of Earth Sciences*, 107(1), 132-146.

Ring, U., Albrecht, C. and Schrenk, F. (2018). The east African rift system: tectonics, climate and biodiversity. In Mountains, Climate and Biodiversity (eds M. C. Hoorn, A. Perrigo and A. Antonelli), pp. 391– 406. Wiley-Blackwell, John Wiley & Sons, Hoboken.

Röder, A, Stellmes M, Hill J, Kuemmerle T, Tsiourlis GM (2008). Analyzing land cover change using time series analysis of Landsat data and geoinformation processing. A natural experiment in Northern Greece. *Proceedings of SPIE - The International Society for Optical Engineering,* 7104, 1-11. doi: 10.1117/12.800265

Rundel, P.W., Smith, A.P. and Meinzer, F.C. (1994). Tropical Alpine Environments: Plant form and function. Cambridge University Press Cambridge University Press, Cambridge, UK. 376p.

Sala, O.E., Chapin, F.S., Armesto, J.J., Berlow. E., Bloompeld, J., Dirzo, R., et al. (2000). Global biodiversity scenarios for the year 2100. *Science*, 287 (5459), 1770 – 1774. doi:10.1126/science.287. 5459.1770

Sarmiento, G. (1986). Ecological Feature of Climate in High Tropical Mountains. In High Mountains Tropical Biogeography. Eds. Vuilleumier, F. and Monasterio, M. Published by Oxford University Press and the American Museum of Natural History. Oxford University Press. New York. U.S.A. 649p.

Sayre, R., Dangermond, J., Frye, C., Vaughan, R., Aniello, P., Breyer, S., Cribbs, D. et al. (2014). A New Map of Global Ecological Land Units – An Ecophysiographic Stratification Approach. Washington, DC: Association of American Geographers.

Sayre, R., Frye, C., Karagulle, D., Krauer, J., Breyer, S., Aniello, P., et al. (2018). A New High-Resolution Map of World Mountains and an Online Tool for Visualizing and Comparing Characterizations of Global Mountain Distributions. *Mountain Research and Development*, 38(3), 240 - 249. doi.org/ 10.1659/MRD-JOURNAL-D-17-00107.1

Scherrer, D., and Korner, C. (2011). Topographically controlled thermal-habitat differentiation buffers alpine plant diversity against climate warming. *Journal of Biogeography*, 38 (2), 406 – 416. doi :10.1111/j.1365-2699.2010.02407.x

Schweiger, A.H., Irl, S.D.H., Steinbauer, M.J., Dengler, J., Beierkuhnlein, C. (2016). Optimizing sampling approaches along ecological gradients. Methods. *Methods in Ecology and Evolution*, 7, 463–471. doi:10.1111/2041-210X.12495

Siebert, S., and Ramdhani, S. (2004). The Bale Mountains of Ethiopia. *Veld and Flora*, 54–59.

Sillero-Zubiri C and Macdonald DW (eds.) (1997). The Ethiopian wolf: status survey and conservation action plan. IUCN Canid Specialist Group, Gland, Switzerland and Cambridge, UK. www.canids.org. Accessed on September 20th, 2018.

Singh, V., and Sharma, M.L. (eds.) (1998). Mountain Ecosystems: A Scenario of Unsustainability. Indus Publishing Company. New Delhi.

Sklenar, P., Hedberg, I., and Cleef, A. M. (2014). Island biogeography of tropical alpine floras. *Journal of Biogeography*, 41(2), 287–297. doi.org/10.1111/jbi.12212.

Smethurst, D. (2000). Mountain Geography. *Geographical Review*, 90 (1), 35-56.

Smith, A.P., and Young, T.P. (1987). Tropical alpine plant ecology. *Annual Review of Ecology and Systematics*, 18, 137- 158. doi.org/10.1146/annurev.es.18.110187.001033

Spehn, E. (2011). Mountain Biodiversity: Effects of climate change and how to manage them. *Plant ecology and diversity*, 60, 40-43. doi:10.1080/17550874.2012.698660

Stadelbauer, J. (2008). Diversity in Mountain Systems: An Introduction. In Löffler, J., and Stadelbauer, J. Diversity in Mountain Systems. *Colloquium Geography*, 31: Asgard-Verlag Dr. Werner Hippe GmbH. Sankt Augustin. Germany. 171p.

Stattersfield, A.J., Crosby, M.J., Long, A.J., and Wege, D.C. (1998). Endemic Bird Areas of the World. Priorities for Biodiversity Conservation. BirdLife Conservation Series No. 7. BirdLife International, Cambridge, UK. 860p.

Steinbauer, M., Irl, S., and Beierkuhnlein, C. (2013). Elevation-driven ecological isolation promotes diversification on Mediterranean islands in. *Acta Oecologica - International Journal of Ecology*, 47, 52-56. doi.org/10.1016/j.actao.2012.11.004.

Steinbauer, M.J., Field, R., Grytnes, J.A., Trigas, P., Ah-Peng, C., Attorre, F., et al. (2016a). Topography-driven isolation, speciation, and a global increase of endemism with elevation. *Global Ecology and Biogeography,* 25 (9), 1097-1107. doi.org/10.1111/geb.12469.

Steinbauer, M.J., Grytnes, J.A., Jurasinski, G., Kulonen, A., Lenoir, J., Pauli, H., et al. (2018). Accelerated increase in plant species richness on mountain summits is linked to warming. *Nature*, 556(7700), 231-234. doi.org/10.1038/s41586-018-0005-6.

Steinbauer, M.J., Irl, S.D.H., Gonzalez-Mancebo, J.M., Breiner, F.T., Hernandez-Hernandez, R., Hopfenmüller, S., Kidane, Y., Jentsch, A., Beierkuhnlein, C. (2016b). Plant invasion and speciation along elevational gradients on the oceanic island La Palma, Canary Islands. *Ecology and Evolution,* 7 (2), 771-779. doi.org/10.1002/ece3.2640.

Stephens, P. A., d'Sa, C. A., Sillero-Zubiri, C., & Leader-Williams, N. (2001). Impact of livestock and settlement on the large mammalian wildlife of Bale Mountains National Park, Southern Ethiopia. *Biological Conservation*, 100, 307–322. doi:10.1016/S0006-3207(01)00035-0.

Taddese, G. (2001). Land Degradation: A challenge to Ethiopia. *Environmental Management*, 27, 815-824.

Testolin, R., Attorre, F., Borchardt, P., Brand, R.F., Bruelheide, H., Chytrý, M., De Sanctis, M., Dolezal, J., Finckh, M., Haider, S., et al. (2021). Global patterns and drivers of alpine plant species richness. *Global Ecology and Biogeography*, 2021(30), 1218–1231. doi: 10.1111/geb.13297.

Troll, C. (1973). High Mountain Belts Between the Polar Caps and the Equator: Their Definition and Lower Limit. *Arctic and Alpine Research,* 5(sup3), A19 - A27. doi: 10.1080/00040851.1973.12003713

Troll, C. and Lauer, W. (eds.), (1978). Geoecological Relations between the Southern Temperate Zone and the Tropical Mountains. Erdwissenschaftliche. Forschung, Der Akademie der Wissenschaften und der Literatur, Mainz. Franz Steiner Verlag, Wiesbaden, GMBH, Stuttgart, 563p.

Uhlig, S., Uhlig, K. (1991) Mountain Chronicles. Studies on the Altitudinal Zonation of Forests and Alpine Plants in the Central Bale Mountains, Ethiopia. *Mountain Research and Development,* 11, 153-256.

Uhlig, S.K. (1990). Mountain Forests and the Upper Tree Limit on the Southeastern Plateau of Ethiopia. In Messerli, B., Hurni, H. (Eds.). (1990). African Mountains and Highlands: Problems and Perspectives. Walsworth Press Co., Inc., Missouri. 450p.

Umer, M., Lamb, H.F., Bonnefille, R., Lezine, A.M., Tiercelin, J.J., Gibert, E., Cazet, J.P., Watrin, J. (2007). Late Pleistocene and Holocene vegetation history of the Bale mountains, Ethiopia. *Quaternary Science Reviews*, 26 (17-18), 2229-2246. doi.org/10.1016/j.quascirev.2007.05.004

United States Geological Survey (USGS) (2009). Landsat Archive. Landsat standard data products. http://landsat. usgs.gov. Accessed 20 Sept 2010 and July 2017.

Van der Putten, W.H., Macel, M., and Visser, M.E. (2010). Predicting species distribution and abundance responses to climate change: why it is essential to include biotic interactions across trophic levels. *Philosophical Transactions of The Royal Society B Biological Sciences,* 365(1549), 2025-2034 doi:10.1098/rstb.2010.0037

Viviroli, D., Archer, D. R., Buytaert, W., Fowler, H. J., Greenwood, G. B. et al. (2011). Climate change and mountain water resources: overview and recommendations for research, management and policy. *Hydrology and Earth System Sciences*, 15(2), 471-504. doi.org/10.5194/hess-15-471-2011.

Walther, G.R., Post, E., Convey, P., Menzel, A., Parmesank, C., Beebee, T.J.C., Fromentin, J.M., Hoegh Guldberg, O., Bairlein, F. (2002). Ecological responses to recent climate change. *Nature,* 416, 389-395. doi.org/10.1038/416389a.

Wegmann, M., Leutner, B., and Dech, S. (2016). Remote Sensing and GIS for Ecologists: Using Open Software. Exeter: Pelagic Publishing, UK. 333p.

Wesche, K. (2003). The importance of occasional droughts for Afroalpine landscape ecology. *Journal of Tropical Ecology,* 19(2), 197-208. doi.org/10.1017/S0266467403003225

Wesche, K., Cierjacks, A., Assefa, Y., Wagner, S., Fetene, M., and Hensen, I. (2008). Recruitment of trees at tropical alpine treelines: Erica in Africa versus Polylepis in South America. *Plant Ecology and Diversity*, 1(1), 35–46. doi.org/10.1080/17550870802262166

Wesche, K., Miehe, G., and Kaeppeli, M. (2000). The significance of fire for Afroalpine Ericaceous vegetation. *Mountain Research and Development*, 20, 340-347. doi.org/10.1659/0276-4741(2000) 020[0340:TSOFFA]2.0.CO;2

Whittaker, R.H. (1975). Communities and Ecosystems. 2nd Revise Edition, MacMillan Publishing Co., NY.ew York. 385p.

Williams, S., Vivero Pol, J.L., Spawls, S., Shimelis, A. and Kelbessa, E. (2004). Ethiopian Highlands. In R.A. Mittermeier, P.R. Gill, M. Hoffmann, J. Pilgrim, T. Brooks, C.G. Mittermeier, J. Lamoreux and G.A.B. Da Fonseca (eds.), Hotspots revisited. CEMEX, Mexico. 200p.

Winkler, M., Lamprecht, A., Steinbauer, K., Hülber, K., Theurillat, J.P., et al. (2016). The rich sides of mountain summit sea pan-European view on aspect preferences of alpine plants. *Journal of Biogeography*, 43 (11), 2261-2273. doi.org/10.1111/jbi.12835.

Woldeghiorgis, W. (2002). Renewable energy for rural development in Ethiopia: the case for new energy policies and institutional reform. *Energy Policy*, 30(11-12), 1095-1105. doi.org/10.1016/S0301-4215(02)00061-7

Woldemariam, M. (1990). An assessment of stress and strain on the Ethiopian highlands. In Messerli, B., Hurni, H. (Eds.). (1990). African Mountains and Highlands: Problems and Perspectives. Walsworth Press Co., Inc., Missouri. 450p.

Woldu, Z., Feoli, E., and Nigatu, L. (1989). Partitioning an elevation gradient of vegetation from south-eastern Ethiopia by probabilistic methods. *Plant Ecology,* 81(1), 189-198. doi:10.1007/BF00045524

Woodward, F.I. (1987). Climate and Plant Distribution. Cambridge University Press. UK. 174p.

Wulff, E.W. (1935). Versuch einer Einteilung der Vegetation der Erde in pflanzengeographische Gebiete auf Grund der Artenzahl. Repert. *Repertorium Specierum Novarum Regni Vegetabilis*, 12, 57-83.

Yineger, H., Kelbessa, E., Bekele, T., and Lulekal, E. (2007). Ethnoveterinary medicinal plants at Bale Mountains National Park, Ethiopia. *Journal of Ethnopharmacology*, 112(1), 55-70. doi:10.1016/ j.jep. 2007.02.001

Yineger, H., Kelbessa, E., Bekele, T., and Lulekal, E. (2008). Plants used in traditional management of human ailments at Bale Mountains National Park, southeastern Ethiopia. *Journal of Medicinal Plant Research*, 2(6), 132-153.

List of Manuscripts and Specification of Own Contribution

The following terminologies are used below in the following sense

- **Data collection** – actual species field data collection, gray literature research, remote sensing image collection
- **Data analysis** – statistical data analysis, modeling, R-script, Remote sensing image analysis, and ArcGIS and QGIS analysis
- **Writing** - formulation of sentences, paragraphs, editing, and formatting
- **Discussions** – conceptualization, hypothesis, and research question, substantiating with literature, comments, and inputs from discussions with the coauthors

Proofreading and language editing was done by professionals for each manuscript.

1. Chapter 1 – (Manuscript 1)

Authors: Yohannes O. Kidane, Reinhold Stahlmann, Carl Beierkuhnlein

Title: **Vegetation dynamics, land use and land cover change (LULCC) in the Bale Mountains of Ethiopia**

Status: Published in Environmental Monitoring Assessment (January 2012)
DOI 10.1007/s10661-011-2514-8 (***Sited more than 139 times to date***)

Contributions:

1. Yohannes O. Kidane: data collection (80%), data analysis (90%), writing (80%), discussions (80%), corresponding author
2. Reinhold Stahlmann: data collection (20%), data analysis (10%)
3. Carl Beierkuhnlein: writing (20%), discussions (20%)

2. Chapter 2 – (Manuscript 2)

Authors: Yohannes O. Kidane, Samuel Hoffmann, Anja Jaeschke, Mirela Beloiu, and Carl Beierkuhnlein

Title: **Ericaceous vegetation of the Bale Mountains of Ethiopia will prevail in the face of climate change.**

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DOI:10.21203/rs.3.rs-620392/v1

Contributions:

1. Yohannes O Kidane: data collection (90%), data analysis (90%), writing (65%), discussions (65%), corresponding author
2. Samuel Hoffmann: data collection (10%), data analysis (5%), writing (5%), discussions (5%),
3. Anja Jaeschke: writing (5%), discussions (5%),
4. Mirela Beloiu: data analysis (5%), writing (10%), discussions (5%),
5. Carl Beierkuhnlein: writing (20%), discussions (20%),

3. **Chapter 3 – (Manuscript 3)**

Authors: Yohannes O.Kidane, Manuel Jonas Steinbauer, and Carl Beierkuhnlein

Title: **Dead end for endemic plant species? A biodiversity hotspot under pressure**

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1. Yohannes O.Kidane: data collection (100%), data analysis (30%), writing (70%), discussions (60%), corresponding author
2. Manuel Jonas Steinbauer: data analysis (70%), writing (20%), discussions (25%)
3. Carl Beierkuhnlein: writing (10%), discussions (15%)

4. **Chapter 4 – (Manuscript 4)**

Authors: Yohannes O Kidane and Carl Beierkuhnlein

Title: **Synergistic impacts of climate and land use land cover (LULC) change on vascular plants diversity and distribution along the Bale Mountains: *hotpot of Afroalpine biodiversity***

Yohannes O Kidane and Carl Beierkuhnlein

Status: In review: Frontiers in Ecology and Evolution

Contributions:

1. Yohannes O. Kidane: writing (75%), discussions (75%), corresponding author
2. Carl Beierkuhnlein: writing (25%), discussions (25%)

Chapter 1

Vegetation dynamics, land use, and land cover change (LULCC) in the Bale Mountains of Ethiopia

Yohannes Kidane[1], Reinhold Stahlmann[1], Carl Beierkuhnlein[1,2,3]

[1]Department of Biogeography, Bayreuth, University of Bayreuth, Germany
[2] Bayreuth Center of Ecology and Environmental Research (BayCEER), Bayreuth, Germany
[3] Geographical Institute Bayreuth (GIB), Bayreuth, German
*** Corresponding author:** Yohannes O Kidane

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ABSTRACT

Shifts in biological communities are occurring at rapid rates as human activities induced global climate change increases. Understanding the effects of the change on biodiversity is important to reduce the loss of biodiversity and mass extinction, and to ensure the long-term persistence of natural resources and nature's services. Especially in remote landscapes of developing countries, precise knowledge about ongoing processes is scarce. Here, we apply Satellite imagery to assess spatiotemporal land use and land cover change (LULCC) in the Bale Mountains for four decades. This study aims to identify the main drivers of change in vegetation patterns and to discuss the implications of LULCC on spatial arrangements and trajectories of floral communities. Remote sensing data acquired from Landsat MSS, Landsat ETM$^+$, and SPOT for four-time steps (1973, 1987, 2000, and 2008) were analyzed using 11 LULC units defined based on the dominant plant taxa and cover types of the habitat. Change detection matrices revealed that over the last 40 years, the area has changed from a quite natural to a more cultural landscape. Within a representative subset of the study area (7,957.5km(-2)), agricultural fields have increased from 1.71% to 9.34% of the total study area since 1973. Natural habitats such as upper montane forest, Afroalpine grasslands, Afromontane dwarf shrubs, herbaceous formations, and water bodies also increased. Conversely, Afromontane grasslands have decreased in size by more than half (going from 19.3% to 8.77%). Closed Erica forest also shrank from 15.0% to 12.37%, isolated Erica shrubs decreased from 6.86% to 5.55%, and Afroalpine dwarf shrubs and herbaceous formations reduced from 5.2% to 1.56%. Despite fluctuations, the Afromontane rainforest (Harenna forest), located south of the Bale Mountains, has remained relatively stable. In conclusion, this study documents a rapid and ecosystem-specific change in this biodiversity hotspot due to intensified human activities (e.g., deforestation, agriculture, infrastructure expansion). Specifically, the ecotone between the Afromontane and the Afroalpine area represents a "hotspot of biodiversity loss" today. Taking into consideration the projections of regional climate warming and modified precipitation regimes, LULCC can be expected to become even more intensive soon. This is likely to impose unprecedented pressures on the largely endemic biota of the area.

Keywords: Biodiversity loss, Vegetation dynamics, Endemism, Elevational gradient, Landuse change, Remote sensing, Tropical mountains

Introduction

Tropical mountain ecosystems are biodiversity hotspots at significant risk in face of land use and land cover change (LULCC) and global warming (Buytaert et al. 2010; Hagedornetal. 2010). In addition to harboring vital diversity for the biosphere, tropical mountains are also hotspots of human activities, thus under increasing pressure from growing populations. LULCC caused by human activities is one of the primary drivers of terrestrial biodiversity change and loss today (e.g., Sala et al. 2000; Rockström et al. 2009). It usually results in habitat loss and fragmentation, local extinction, facilitates invasion by alien species (Lovejoy and Hannah 2005), reduction in soil infiltration rate (Yimer et al. 2008), and variability in soil carbon stock and the emission of other greenhouse gases. In short, LULCC is rapidly transforming many pristine natural habitats beyond their natural range of variability (Hannah et al. 2002; Lovejoy and Hannah 2005). The recent rate of LULCC is extraordinarily high in tropical countries (Foley et al. 2005), including Ethiopia.

Ethiopia features extensive high mountain ecosystems, which represent ecological islands in a tropical to subtropical lowland matrix with differing climates and high land-use pressure. Mountains cover about 43% of the surface of Ethiopia (Woldemariam 1990, cutoff at 1,500m asl). These mountains harbor a remarkable diversity of endemic fauna and flora. The mountain climate is more favorable for many species relative to the lowlands which are predominantly arid and semiarid environments (Hillmann 1990; Messerli et al. 1990). Hence, over 85% of the country's population and over 75% of livestock are estimated to inhabit the Ethiopian mountains today (Amsalu and de Graaff 2006).

As Ethiopia is anciently settled, the question of potential "pristineness" and "naturalness" of ecological systems is difficult to answer (see also Chiarucci et al. 2010). Almost all parts of the country are accessed by humans. Areas of low human impact are confined to the steep escarpments of the Rift Valley, river gorges, cold Afroalpine plateaus, and some sacred areas (Gebregziabher 1991). Yet evidence suggests that despite this long history of human impacts, LULCC has accelerated dramatically in recent years, progressively depleting the vegetation (NBSAP 2005). Furthermore, as pointed out in Kreyling et al. (2010), this loss is expected to be exacerbated by future climate change. Quantification of LULCC in this unique and highly threatened ecosystem is thus extremely urgent.

The assessment of LULCC has emerged as a fundamental component of global change research (Turner et al. 2007). It is multidisciplinary in its approach and seeks to understand dynamics in a coupled human-environment system (Turner et al. 2007; Olson et al. 2008). Here, remote sensing data spanning ~40 years have been used to quantify for the first time LULCC impacts on temporal vegetation dynamics in the Bale Mountains of Ethiopia. The goal is to identify the main local drivers of changing vegetation patterns during this time interval and inform how continued LULCC will impact the spatial arrangements and trajectories of floral communities with future climate change.

The Bale Mountains of Ethiopia are of global conservation significance (Hillman 1986). They are home to the largest population of the endangered endemic Ethiopian Wolf (*Canis simensis*) and of Mountain Nyala (*Tragelaphus buxtoni*) (Sillero-Zubiri & Macdonalds 1997). The mountains also host a number of unique plants such as Lobelias (e.g. *Lobelia rhynchopetalum, Lobelia scebelii* and *Lobelia giberroa*) and *Senecio* species (e.g. *Senecio nanus, Senecio fresenii, Senecio inornatus, Senecio ochrocarpus, Senecio ragazzi, Senecio schultzii, Senecio subsessilis* and *Senecio unionis*). Besides, the endemic plant populations of mountains are important reservoirs of genetic diversity (Hillmann 1988; Uhlig 1990; NBSAP 2005). The rainforests located to the south represent the native habitat of wild coffee. Additionally, the mountains support numerous ecosystem services for lowland areas including capture, distribution, and regulation of the water supply.

Until the early 1960s, the Bale Mountains area was sparsely populated (Stephens et al. 2001). Hence, the population pressure in the area was low. In 1971 the Bale Mountain National Park (BMNP) was established, covering a large portion of the massif. It comprises an area of 2,200km^2 of Afroalpine habitat and includes part of the Afromontane rainforests. The establishment of this park was targeted at protecting the Afroalpine habitat and its endemic mammalian fauna (Hillman 1988). Today, BMNP is listed as one of the UNESCO 200 worldwide Bioregions (Umer et al. 2007) and represents a potential world heritage site. Furthermore, the Afroalpine ecosystems of the massif are one of 34 recognized Conservation International Biodiversity Hotspots (CIBH) and are listed as an Important Bird Area (IBA) by Birdlife International (NBSAP 2005).

Ecological studies of the Bale Mountains focus on documenting the biodiversity, fauna, and flora of the area (e.g., Bonnefille 1983; Gebregziabher 1988, 1991; Woldu et al. 1989; Messerli et al. 1990; Uhlig 1990; Uhlig and Uhlig 1991; Friis 1992; Miehe and Miehe 1994; Mohamed-Saleem and Woldu

2002; Darbyshire et al. 2003; Umer et al. 2007). Some studies focused on issues of exploitation, degradation, and management (e.g., Getahun 1984; Messerli et al. 1990; Grepperud 1996; Taddese 2001; Amente 2005). Wesche et al. (2000) and Wesche (2003) have investigated the role of fire and drought. Until now, there has been no integrated quantitative assessment of how biodiversity and LULCC developed over time.

Material and methods

Study area

Orography

The Bale Mountains are located in southeast Ethiopia in the Oromia regional state (Fig.1), between 06°29′N, 39°03′E and 07°10′N, 40°00′E. The mountains comprise one of the most extensive high-altitude plateaus (above 3,000m in elevation), the largest contiguous mountain massif of over 2,600km^2 in Africa, and one of the last remaining pristine Afroalpine biodiversity hotspots on the continent (Hillman1988; Laurenson et al. 1998). The massif exhibits a steep gradient of ecological zones ranging from lowland semideserts, savannas and grasslands, and tropical rainforests to Afroalpine vegetation. At the plateau, there are several high peak summits. The highest point mount Tullu Deemtu reaches 4,385m asl of the massif.

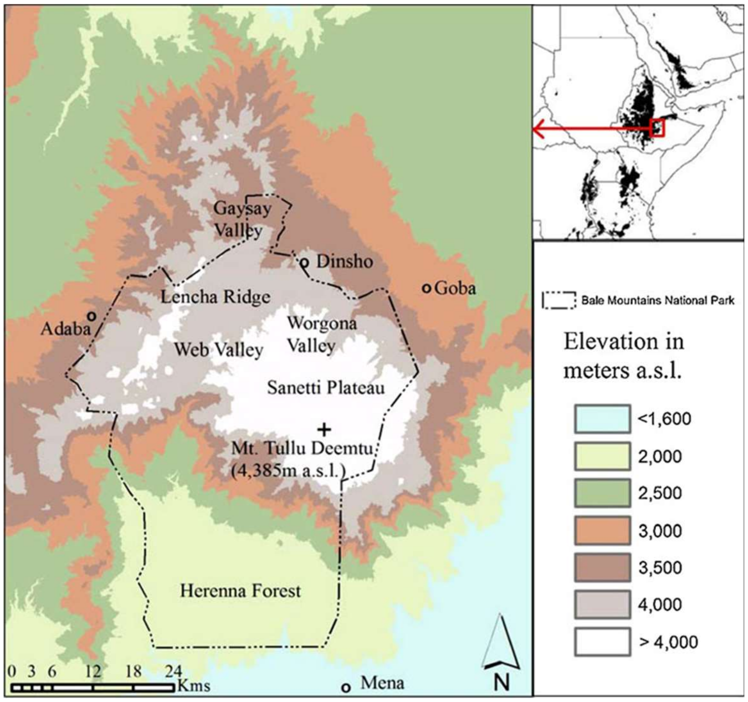

Fig.1: The study area with the borders of the Bale Mountains National Park. The extents of major altitudinal gradients in meters above sea level and important locations are indicated. The whole area above 4,000m is the Sanetti plateau which is the main Afroalpine zone.

Climate

The Bale Mountains are located at the convergence of the wet east African and dry northeast African mountains of southeast Ethiopia. The climate of the mountains varies from north to south mainly due to the differences in elevation, aspect, and the influences of lowland hot air masses (Uhlig 1990). Historically, the area has experienced a high degree of climate variability and change (Umer et al. 2007). These past climatic changes have played a crucial role in shaping contemporary vegetation. The current climate is characterized by a short dry season (November to February) and a long period of rainfall and high moisture (March to October). The wet season rainfall pattern is slightly bimodal, with a peak from April to May followed by a second peak from September to October (Woldu et al. 1989). Recently, the area has also witnessed an increase in the frequency and severity of exceptional droughts (e.g., the year 2000 see Wesche2003).

Rain comes to the Bale Mountains from two different sources: the equatorial westerly and the Indian Ocean monsoon (Uhlig 1990; Miehe and Miehe 1994). Along with altitude, precipitation increases up to an elevation of 3,850m asl but decreases then again towards the summits (Hillman 1986). The northern part of the mountain range exhibits 800 - 1,000 mm of annual rainfall and a wet season from June to September. The southern part is more humid, with a subtropical climate and 1,000 - 1,500mm of annual rainfall (Woldu et al. 1989).

The Afroalpine habitats are characterized by strong diurnal temperature fluctuations and night frost. On the Sanetti Plateau, Hillmann (1990) recorded extremes of a diurnal temperature range of 40°C (-15°C to +26°C) during the dry season. The diurnal amplitude in temperature varies between the wet and dry seasons. The wet season is warmer at night and cooler by day compared to the dry season (Admasu et al. 2004). Here, the coldest time of the year is also the driest, the main wet season being associated with the convergence of northeast and southwest airstreams (Bonnefille 1983). Consequently, the biota experience extreme temperature variation within each 24-h period during the whole year, experiencing "summer every day and winter every night" (Hedberg 1964).

Geology and geomorphology

The Bale Mountains are fragmented due to numerous volcanic plugs, peaks, alpine lakes, and rushing mountain streams that descend into deep rocky gorges on their way to the lowlands. The uppermost part, the Sanetti plateau, is an isolated area covering 211km^2 at an altitude of about 4,000m bordered by abrupt escarpments to the south. The north and northeast are deeply dissected valleys descending to the northern slope, while to the west lava flows form spectacular bluffs (Osmaston et al. 2005).

Bale Mountain geology is characterized by a high-altitude volcanic plateau over much older volcanic material formed during the spreading of the EastAfrican Rift Valley system. The petrography is dominated by alkali basalt and tuffs, with occasional rhyolites (Uhlig and Uhlig 1991). The mountains were locally glaciated, which shaped their recent geomorphology (Osmaston et al. 2005).

Soils in the area tend to be shallow, gravelly, and recently derived from volcanic rock exposed since glacial retreat (Sillero-Zubiri and Macdonald 1997). Soils consist of a relatively silty loam of reddish-brown to black color (Woldu et al. 1989). Soils located on top of stratigraphically youngest units derive mainly from the Miocene basalt and trachyte lavas that lay over Mesozoic sediments (Umer et al. 2007).

Data collection

We focus on a subset area of the Bale Mountains that ranges from 39°39′E/7°39′N and 40°09′E/6°47′N. Data consist of preprocessed Landsat and SPOT images of four-time steps (1973, 1987, 2000, and 2008). The Landsat Multispectral Scanner (MSS) and Enhanced Thematic Mapper Plus (ETM+) data were acquired from the United States Geological Survey (USGS) *EarthExplorer* homepage (http://edcsns17.cr.usgs.gov/NewEarthExplorer). SPOT images from February 2008 were acquired from SPOT Planet action (http://www.planet-action.org; **Fig. 2**). We chose high-resolution (2.5m) SPOT data instead of more recent Landsat images for the 2008 time slice due to the known failure of the Scan-Line Protector onboard Landsat 7 on May 21, 2003 (USGS 2009).

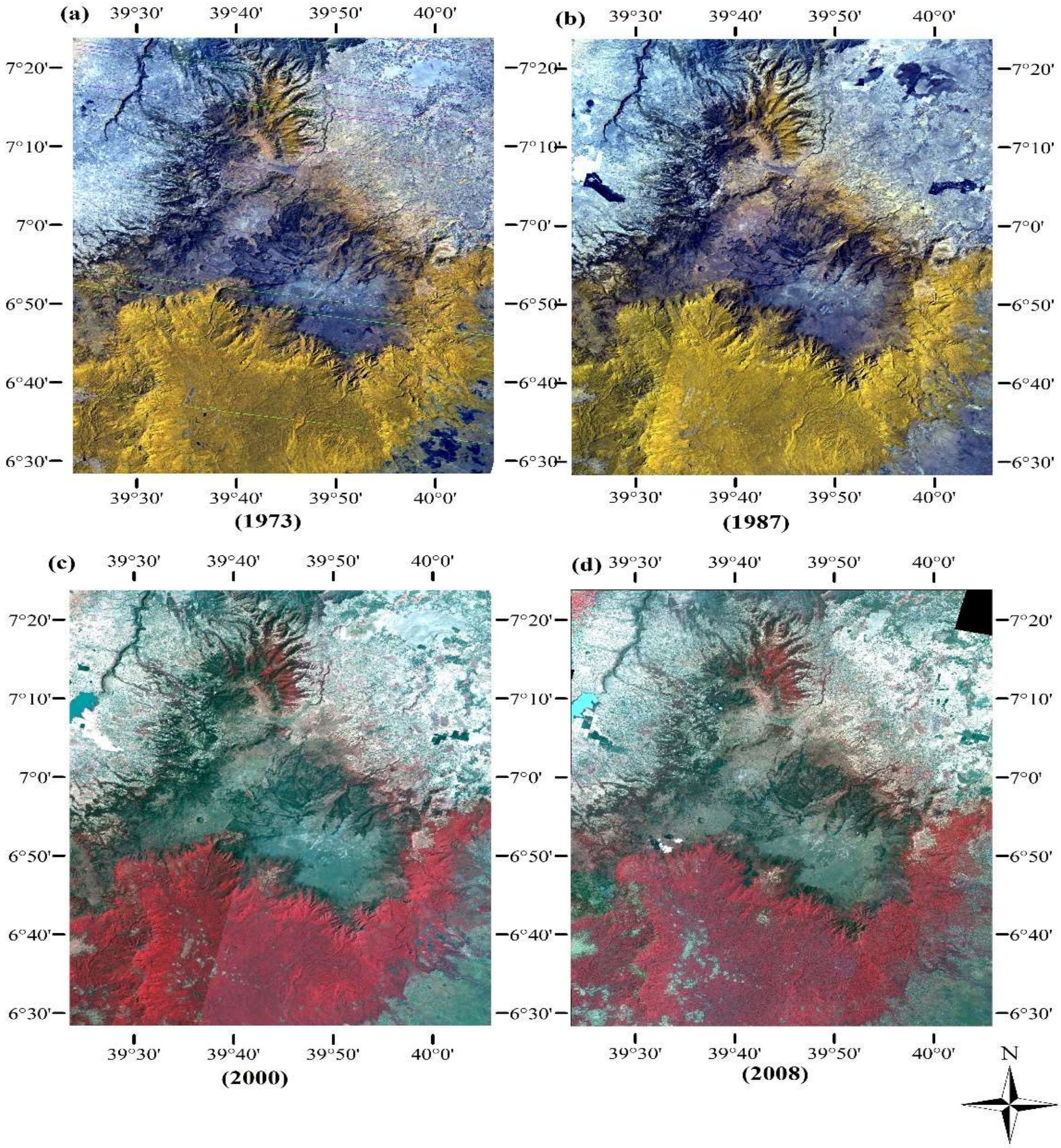

Fig. 2 Time series of raw satellite images used for the analysis with their respective year of acquisition. **a)**The 1973 MSS image of path 180 and row 055; **b)** the 1987 MSS image of paths 167and 168, and row 055; ***c***) the 2000 ETM + image of paths 167and 168, and row 055; and **d)** the 2008 SPOT_5 image with path138 to 142 and rows 135 to 137.

All images selected for analysis were from the end of the dry season (end of January and beginning of February, **Table 1).** Dry season images are preferable because they are more likely to be cloud-free and their spectral properties are less affected by moisture. Seasonal and sensor coherence allows mapping similar vegetation phenology and similar atmospheric conditions to reduce sun angle differences and to match spectral characteristics of various habitats through time and cover types (Lu et al. 2004).

Table 1: The Landsat and SPOT images used: with scene ID, image acquisition date, and respective satellite model and type.

Scene ID	Date	Satellite
Path 180, Row 055	January 30th 1973	Landsat1 WRS-1 (Worldwide Reference System)
Paths 167 & 168, Row 055	February 2nd 1987 and February 9th 1987	Landsat5 WRS
Paths 167 & 168, Row 055	February 14th 2000 and February 5th 2000	Landast7 WRS2
Paths 139-142, Rows 335 to 337	February 4th 2008	SPOT-5

The Landsat MSS images record radiation averaged over 80×80m cells, with four bands of spectral coverage ranging from the visible green to the near-infrared (IR). The Landsat ETM+ data record radiation reflected from 30×30m cells on the ground, with seven bands including visible and IR bands. Both scan a 185-km swath of the Earth’s surface as the satellite successive orbits, with a complete reflectance data set compiled over a 16 - day repeat cycle. The SPOT-5 images record radiation collected on 2.5×2.5m cells on the ground of three bands with a revisit time of 2–3 days, depending on latitude.

Image processing and analysis

Image processing

LULCC detection requires both image registration and similar class comparison over time and space. Prior to determining the changes between different images, the following important processing steps were completed: georeferencing, coregistration, and spectral calibration of the image data set. These steps are critical to the success of multitemporal remote sensing studies (Elmore et al. 2000).

The spatial data were available in the Universal Transverse Mercator (UTM) coordinates system and were subsequently converted to Geographic Lat/Long WGS-84. The altitudes were delineated in a Geographic Information System (GIS) using 90 m Shuttle Radar Topography Mission (SRTM) digital elevation model data from the USGS. Image coregistration was carried out to remove overlap areas and the scenes were layer-stacked together to create composite spectral bands. The bands used for the Landsat are the vegetation-sensitive Near Infrared (VNIR) bands: band 2 (0.58 - 0.68μm), band 3 (0.69 - 0.83μm), and band 4 (0.5 - 0.6μm) of the MSS, band 3 (0.69 - 0.83μm), band 5 (0.6 - 0.7μm) and band 7 (0.8 - 1.1μm) ETM+, and bands Red (0.61 - 0.68μm), Near IR (0.78 - 0.89μm) and Shortwave IR (1.58 - 1.75μm) for the SPOT. The color composite of the three bands was used as a background during georeferencing and image classification. Images were then thematically classified based on the vegetation cover types and other land surface properties.

Image classification and accuracy assessment

Image classification and evaluation were carried out by ENVI-IDL software. Here the multitemporal image processing chain, an object-based supervised maximum likelihood classification algorithm, was used. In such an approach, the analyst defines areas where the land cover is known, predefines the LULC types, and the number of classes based on selected parameters. This approach enhances the delineation objectivity, interpretation repeatability, and processing efficiency (Duveiller et al. 2008).

Classification identified 11 predominant LULC classes that represent the major LULC types of the area. Descriptions of these classes are given in **Table 2.** Classes are arranged along an elevational sequence of LULC types.

Table 2: The eleven most prominent LULC classes of the Bale Mountains area that were used for the classification and their short description.

No.	Classes	Code	Description
1	**Afroalpine grasslands (Tussock grasslands)**	T_g	Extensive grasslands dominated by grasses (principally *Festuca richardii*) with large number of herbaceous species at the afroalpine region.
2	**Afroalpine dwarf shrubs and herbaceous formations**	A_{dh}	Located above the forest, Afroalpine vegetation, including the dwarf shrubs *Helichrysum splendidum*, *Alchemilla haumanii*, and the Giant Lobelia (*Lobelia rhynchopetalum*).
3	**Isolated Erica shrubs**	E_i	Comprises small Erica groves within afroalpine *Helichrysum* heath and fire relics. Frequent bush fire affected vegetation. The Erica is kept in low (1-3m), shrubby regeneration phases. Dominated with dark-green *E. trimera* restricted to distinct patches or solitary individual shrubs (Miehe and Miehe 1994; Umer et al. 2007)
4	**Erica forest**	E_f	Usually referred as Ericaceous belt comprises forest, thickets and scrublands of *Erica trimera* and *arborea* communities. *E. trimera* forms trees up to 15m tall with abundant epiphytes, especially the moss *Antitrichia curtipendula* and the lichen *Usnea articulata*. *E. trimera* canopy height diminishes further with increasing altitude and grasses and mosses predominate in the ground layer (Miehe and Miehe 1994; Umer et al. 2007).
5	**Uppermontane forests**	F_{um}	*Hagenia* and *Hypericum* zone. It is dominated by 12-18m tall *H. revolutum* and *Rapanea melanophloeos*, accompanied by *Schefflera* and bamboo (*Sinarundinaria alpina*), with emergent *H. abyssinica* up

			to 25m tall. Bamboos found in the form of different patches here. (Miehe and Miehe 1994; Umer et al. 2007).
6	**Afromontane rainforest**	**F_r**	Located mainly at the southern slopes is the tropical rainforest, which receives rainfall for more than eight months a year. It is dominated by *Podocarpus* associated with *Syzygium guineense* and *Aningeria adolfi-friederici* (Miehe and Miehe 1994; Umer et al. 2007).
7	**Afromontane dwarf shrubs and herbaceous formations**	**S_{dh}**	Mainly Shrub and bushland dominated by *Dononea angustifolia, Dichrostachys cinerea* shrubs, Acacia spp. (*Acacia mellifera*), Erica spp., tufted grasses (principally *Festuca richardii*) and other thorny species and large number of herbaceous species (Miehe and Miehe, 1994; Umer et al. 2007).
8	**Afromontane grasslands**	**G**	Extensive grasslands dominated by grasses with sparse trees and shrubs along the afromontane range. The dominant grass species include *Themeda triandra*, *Hyparrhenia spp*., *Heteropogon contortus* and scattered tress of *Acacia mellifera*, and *Dichrostachys cinerea.*
9	**Agricultural lands**	**Ag**	The Croplands mainly planted cereals such as Tef (*Eragrostis tef*), barely (*Hordeum vulgaris*), maize (*Zea meays*) and wheat (*Triticum Spp*.). Includes irrigated croplands such as mechanized agriculture (with cotton, sugar cane, coffee, orange and banana plantations) mostly state owned, and rainfed croplands (with annual and perennial crops) usually owned by local farmers and small landholders
10	**Barren and burned areas**	**B**	Comprises exposed rocks, bare ground due land clearing, burning, fallowing, or excessive erosion and sedimentations.
11	**Water bodies**	**W**	The afroalpine lakes, the rivers and the hydroelectric dam

The quality of post-classification change detection techniques depends on the generation of accurately classified images (Wickware and Howarth 1981). According to Foody (2002), classifications are not free from errors. In remote sensing classification, there is a need to identify both training and test data sets. Training data are required to fit the classification algorithm to local conditions and testing data are required to assess the accuracy of the final classification (Atkinson et al. 2007). Before a classification is completed, several iterations of cross-validation are conducted. This involves modifying the training data until the desired accuracy level is reached, usually above 73% (Foody 2002).

Training areas were identified and investigated based on ground truth information acquired in the area and cross-compared with those from 2.5m SPOT (Feb. 4, 2008), European Space Agency (ESA) Glove cover 2008 classification, *GoogleEarth,* and the local land use classification and descriptions by Hillman (1986, 1990), Uhlig (1990), Miehe and Miehe(1994), and Umer et al. (2007). The accuracy of classification was evaluated using the kappa coefficient, a widely used technique for accuracy assessment. Very good classification accuracy was achieved: kappa coefficient and overall accuracy of 0.76% and 79.4%,0.77% and 81.42%, 0.80% and 83.3%, and 0.82% and 85.4% were achieved for 1973, 1987, 2000, and 2008 images, respectively.

Results

Patterns of change in vegetation and major cover classes

The areal extent of the LULC classes, for each timestep, is summarized in **Table 3**. In the early 1970s, human disturbances were limited (**Fig. 3**). There was no mechanized agriculture in the 1973 image, upper left and right corners of the first image. However, the situation changed in the 1980s mainly due to the introduction of mechanized farming. This is evident from the geometric shapes and sizes of the agricultural fields that are first visible in the 1987 time slice. Likewise, in the late 1980s, the Melka Wakena hydroelectric dam was constructed and intensive resettlement and villagization programs were implemented (Hillmann 1990).

Table 3: The eleven landscape level LULC classes and their spatial extent with the observed changes over time.

Land Use Land Cover classes	**Code**	**1973**		**1987**		**2000**		**2008**	
		Area (Km^2)	**percent**	**Area (Km^2)**	**percent**	**Area(Km^2)**	**Percent**	**Area (Km^2)**	**Percent**
Agricultural lands	**Ag**	136.39	1.71	572.19	7.19	1,362.94	17.1	735.39	9.24
Afromatane grassland	**G**	1,538	19.3	1,499.12	18.84	539.81	6.79	697.58	8.77
Afromontane rainforest	**F_r**	2,545	31.98	2,111.8	26.54	2,482.47	31.2	2,527.67	31.77
Uppermontane forest	**F_{um}**	641.19	8.06	720.9	9.06	1,038.93	13.06	1,005.93	12.64
Ericaceous forest	**E_f**	1193.93	15	1,569.06	19.8	747.84	9.4	984.29	12.37
Isolated Erica shrubs	**E_i**	545.62	6.86	502.3	6.3	250.7	3.15	441.35	5.55
Afromontane dwarf Shrubs and herbaceous formations	**S_{dh}**	544.3	6.84	353.4	4.44	577.74	7.26	729.28	9.17
Barren and burned areas	**B**	350.59	4.4	229.16	2.88	648.84	8.15	259.65	3.26
Afroalpine grasslands (Tussock grasslands)	**Tg**	47.89	0.6	66.08	0.83	80.88	1.02	272.25	3.42
Afroalpine dwarf shrubs and herbaceous formations	**Adh**	414.14	5.2	327.75	4.12	211.70	2.66	123.88	1.56
Water bodies	**W**	0.8	0.01	5.98	0.08	15.62	0.2	62.78	0.79
No data		0.00	0.00	0.00	0.00			117.44	1.48
Total		7957.85	100	7957.74	100	7957.47	100	7957.49	100

NB: *The different LULC classes are coded for convenience reasons to easily fit the columns of the change detection matrix. The code will be used consistently in the following sections.*

During the ~ 40-year study period, Afromontane habitats have lost considerable area to agriculture. Agricultural land has expanded from 136.39km^2(1.71%) in 1973 to 572.19km^2 (7.19%) in 1987, at the expense of Afromontane grasslands and Afromontane dwarf shrubs and herbaceous formations. This expansion continued during the second period (from 1987 to 2000), with agricultural land expanding to 1,362.94km^2 (17.1%). During the third period (between 2000 and 2008), agricultural land reduced again to 735.39 km^2. This recent reduction accounts mainly for the abandonment or fallowing of large state farms in the northern part of the study area.

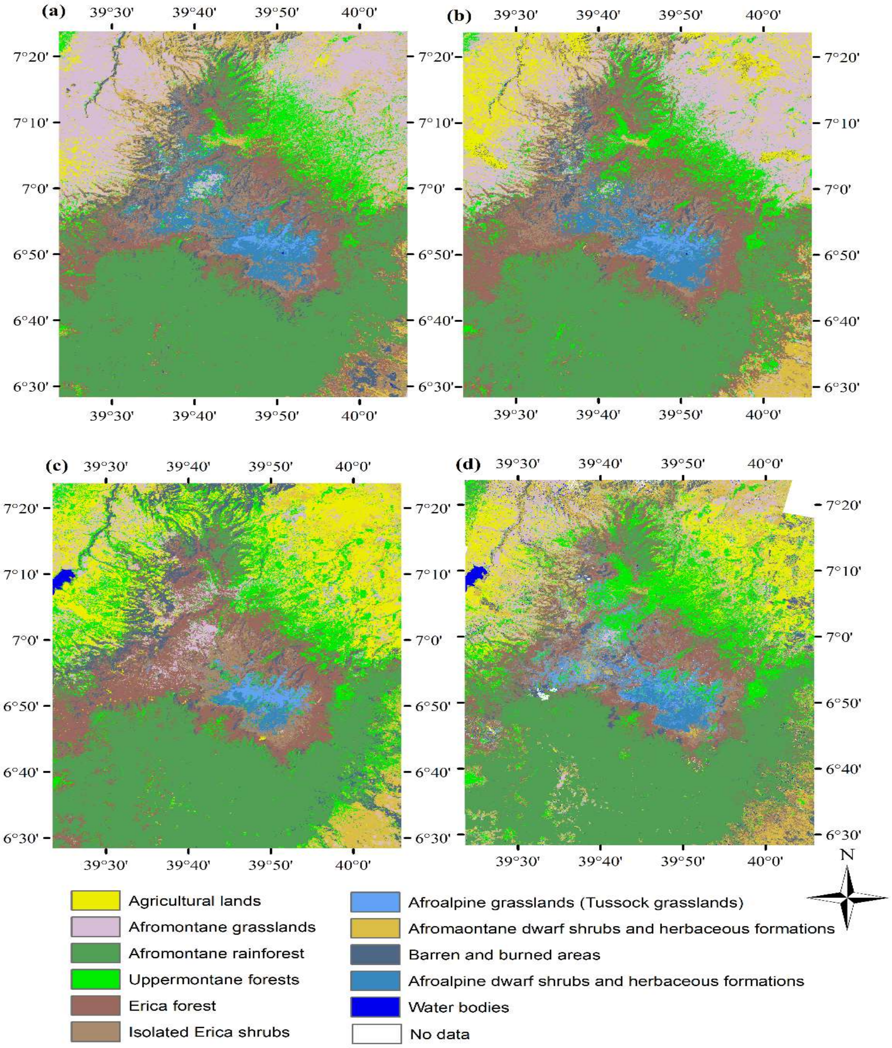

Figure 3: Time series of the classified Landsat scenes with the eleven most prominent LULC classes.

Some LULC classes such as upper montane forest expanded strongly in size during the last decades (from 641.19 to 1,005.93km^2). Afromontane dwarf shrubs and herbaceous formations increased from 544.3 to 729.28km^2, Afroalpine grasslands (tussock grasslands) increased from 47.89 to 272.25km^2, and water bodies increased from 0.08 to 0.79km^2. The increase in water bodies over this interval can be attributed to the construction of the Melka Wakena dam. Concomitantly, Afromontane grasslands have reduced from 1,538 to 697.58km^2, *Erica* forest decreased from 1,193.93 to 984.29km^2, isolated Erica shrubs decreased slightly from 545.62 to 441.35km^2, and Afroalpine dwarf shrubs and herbaceous formations declined from 414.14 to 123.88km^2. The Afromontane rainforest remained more or less constant in space over the 40-year study period despite some minor fluctuations (was 2,545km^2 in 1973 and was still 2,527.67km^2).

Change detection matrix

While visual and tabular comparison of changes in total coverage of LULC types over time can provide primary qualitative insights into the degree of change experienced by an area, pixel-based statistical analyses, such as change detection matrices, allow a more rigorous quantitative analysis of LULCC trends over time. This approach measures the change dynamic in each cell for all LULC classes. Class-to-class changes, as well as total gains and losses of specific LULC types, can be detected. A prerequisite for the application of change detection matrices is a similar spatial resolution of geoinformation when comparing onetime step with the next (Alphan et al. 2009). The Landsat ETM+ 30m image of 2000 and the SPOT images of 2.5m 2008 were resampled to 80m resolution in order to match the pixel size of the Landsat MSS (1973 and 1987) images. First, change detection statistics were calculated independently for all timesteps. Second, the classified four pairs of images representing 1973 and 2000, 1973 and 1987, 1987 and 2000, and 2000 and 2008 were cross-tabulated.

The overall change detection matrix, for the complete time series between 1973 and 2008, shows that most of the LULC classes are losing some of their previous areas to agricultural land, Afromontane grassland, upper montane forest, and water bodies. A total of 26.65% of the original area of Afromontane grasslands, a total of 15.41% of upper montane forest, and a total of 14.58% of Afromontane dwarf shrubs and herbaceous formations were converted to agricultural lands. In addition, Afromontane grasslands gained 11.59% from upper montane forest. Upper montane forest gained 5.94% from *Erica* forest. *Erica* forest gained 11.93% from isolated *Erica* shrubs. Afromontane grasslands gained a total of 32.93% of area from agricultural land. Upper montane forest lost 18.52% of their original area to *Erica* forest, while gaining considerable area from Afromontane grasslands (9.82%), Afromontane rainforest (6.53%), and Afroalpine grasslands 13.46% (**Table 4**).

Agricultural lands have gained 599km^2 over this interval more than tripling their original size. Afromontane grasslands gained 50.43km^2, upper montane forest gained 182.73km^2, *Erica* forest gained 364.74km^2, Afromontane dwarf shrubs and herbaceous formations 224.36km^2, and water bodies 61.98km^2. While *Erica* forest lost 209.64km^2, isolated *Erica* shrubs lost 104.27km^2, Afromontane dwarf shrubs and herbaceous formation lost 184.98km^2**.**

Table 4: The calculated change detection matrix, in percent, covers the change of the whole study period from 1973 to 2008.

		Initial State (1973)										
	LULC Classes	**Ag**	**G**	**Fr**	**Fum**	**E_f**	**E_i**	**S_{dh}**	**B**	**Adh**	**Tg**	**W**
Final State (2008)	**Ag**	**35.40**	32.93	0.18	13.46	0.82	0.53	13.44	0.71	0.30	0.84	0.68
	G	26.65	**29.77**	0.75	9.82	1.83	2.26	14.16	0.77	1.84	0.00	3.40
	F_r	1.95	0.72	**84.79**	6.53	19.47	3.85	3.78	11.01	0.37	0.00	2.72
	F_{um}	15.41	11.59	3.28	**49.95**	18.52	3.4	16.41	1.58	14.27	19.45	4.76
	E_f	0.80	1.0	6.67	5.94	**32.08**	28.93	6.72	40.44	9.71	1.25	4.76
	E_i	0.18	0.62	1.05	1.91	11.93	**23.71**	4.63	12.84	12.11	1.12	13.61
	S_{dh}	14.58	13.97	2.15	8.03	6.26	15.53	**28.73**	12.93	6.52	0.00	34.02
	B	1.34	2.49	0.76	1.55	4.0	8.37	6.16	**15.67**	1.94	0.52	14.29
	Adh	0.00	0.00	0.00	0.05	0.27	2.47	0.00	0.18	**23.00**	23.14	0.68
	Tg	0.09	0.59	0.03	1.53	3.82	9.47	0.03	2.20	29.49	**52.72**	7.48
	W	1.77	2.14	0.22	0.54	0.39	0.52	1.79	0.17	0.11	0.37	**8.16**
	No data	**1.86**	**4.21**	**0.12**	**0.71**	**0.63**	**0.98**	**4.17**	**1.51**	**0.35**	**0.60**	**5.44**
	G/L	**440.01**	**-54.64**	**-0.68**	**56.89**	**-17.56**	**-19.11**	**33.99**	**-25.94**	**-70.09**	**468.52**	**7738.1**
	Cl.Ch	**64.60**	**70.23**	**15.21**	**50.05**	**67.92**	**76.29**	**71.27**	**84.33**	**71.0**	**47.29**	**91.84**

G/L Gain/Loss in km^2 **Cl. Ch.** Class change in percent

Within this 40-year period of LULCC, fine-scale and short-term dynamics of changing LULC classes can be identified through the analysis of individual time steps. The change matrix for the first time step (1973 to 1987) is detailed in **Table 5**. Here, the most considerable change that occurred is the reduction of Afromontane grasslands by 56.09% of their original area to agricultural lands. During this time interval agriculture started to expand to higher altitudes taking area from the upper montane forest (5.22%), while other cover types did not show a notable conversion to agricultural land. Interestingly, during the same period, grasslands gained 26.41% in area from croplands, perhaps due to the abandonment of former farmlands.

Table 5: The cross-tabulated change detection matrix, in percent covers change, of the first time step 1973 to 1987.

		Initial State (1973)										
	LULC Classes	**Ag**	**G**	**Fr**	**Fum**	**E_f**	**E_i**	**S_{dh}**	**B**	**A_{dh}**	**Tg**	**W**
Final State (1987)	**Ag**	**33.34**	26.41	0.07	1.88	0.19	1.55	13.17	6.33	0.53	0.05	7.48
	G	59.09	**63.21**	0.18	28.71	1.44	3.08	37.91	2.66	2.0	0	5.44
	F_r	0	0.02	**80.01**	0.99	4.91	0.15	0.1	2.51	0	0	0
	F_{um}	5.22	4.57	3.08	**48.48**	12.32	1.56	11.06	1.98	7.0	5.28	4.76
	E_f	0.17	1.11	14.87	15.11	**63.21**	18.61	9.88	22.06	21.06	3.73	6.12
	E_i	0.3	0.72	0.51	0.59	9.91	**40.39**	5.74	18.25	9.65	0.26	5.44
	S_{dh}	1.21	3.01	0.65	3.17	4.52	13.12	**20.91**	8.21	0.04	0	43.54
	B	0.43	0.32	0.63	0.24	1.61	9.87	0.96	**35.53**	0.75	0.02	2.04
	A_{dh}	0.04	0.59	0	0.67	1.88	11.33	0.03	1.37	**52.47**	16.36	2.04
	Tg	0.06	0	0	0.14	0.02	0.27	0	0.3	6.47	**74.3**	4.76
	W	0.15	0.06	0	0.01	0.01	0.08	0.23	0.81	0.03	0	**18.37**
	G/L	**320.16**	**-2.52**	**-17.02**	**12.43**	**31.42**	**-7.97**	**-35.09**	**-34.64**	**-20.86**	**37.99**	**646.94**
	Cl.Ch	**66.66**	**36.79**	**19.99**	**51.52**	**36.79**	**59.61**	**79.09**	**64.47**	**47.53**	**25.7**	**81.63**

G/L Gain/Loss in km^2 **Cl. Ch.** Class change in percen

The expansion of agricultural lands continued during the second time interval (from 1987 to 2000, Table 6). Afromontane grassland lost 53.58% of its area to agriculture while gaining 21.37% from Afromontane grasslands. Interestingly, during this time interval, agriculture continued to expand to higher altitudes, claiming areas from upper montane forest (4.44%), Afromontane dwarf shrubs and herbaceous formations (5.84%), and from barren and burned areas (6.68%).

Table 6: The calculated change detection matrix, in percent covers change, of the second time step 1987 to 2000.

		Initial State (1987)										
	LULC Classes	**Ag**	**G**	**Fr**	**Fum**	**E_f**	**E_i**	**S_{dh}**	**B**	**Adh**	**Tg**	**W**
Final State (2000)	**Ag**	**57.72**	53.58	0.1	13.64	1.72	4	19.66	3.48	0.99	0.95	20.49
	G	21.37	**20.93**	0.01	6.12	1.06	2.31	4.05	1.04	4.38	0	4.2
	F_r	0.6	1.02	**91.56**	12.74	21.76	3.62	19.30	4.46	0.05	0	4.28
	F_{um}	4.44	11.08	2.26	**46.24**	23.16	4.94	9.46	0.93	12.95	0.32	1.00
	E_f	0.63	0.33	1.63	1.74	**23.83**	41.63	6.13	23.0	10.54	0.81	2.73
	E_i	0.63	0.86	0.03	1.25	4.12	**10.40**	1.63	1.21	28.01	11.12	0.73
	S_{dh}	5.84	10.14	1.69	14.60	7.35	4.35	**31.47**	1.1	0.02	0	7.47
	B	6.68	1.38	2.67	0.92	13.50	24.73	8.29	**64.1**	2.79	3.61	55.28
	Adh	0.13	0.36	0.06	2.47	3.29	3.15	0.02	0.42	**28.74**	36.38	0.73
	Tg	0.14	0	0	0.27	0.23	0.98	0	0.28	11.54	**46.83**	3.1
	W	1.84	0.33	0	0.02	0	0	0	0	0	0	**0**
	G/L	**138.2**	**-63.99**	**17.55**	**44.12**	**-52.34**	**-50.08**	**63.52**	**183.15**	**-35.888**	**22.39**	**161.02**
	Cl.Ch	**42.28**	**79.07**	**8.44**	**53.76**	**76.18**	**89.6**	**68.53**	**35.90**	**71.27**	**53.18**	**100**

G/L Gain/Loss in km^2 **Cl. Ch.** Class change in percent

During the third time step (2000 to 2008; **Table 7**), agricultural lands continue to increase. During this interval, a total of 38.43% of new area from Afromontane grasslands and 4.62% from Afromontane dwarf shrubs and herbaceous formations were converted to agricultural land. Interestingly, agricultural lands lost 11.86% of their original area to upper montane forest and 16.91% to Afromontane dwarf shrubs and herbaceous formations.

Table 7: The calculated change detection matrix, in percent covers change, of the third time step 2000 to 2008.

		Initial State (2000)										
	LULC Classes	**Ag**	**G**	**Fr**	**Fum**	**E_f**	**E_i**	**S_{dh}**	**B**	**Adh**	**Tg**	**W**
Final State (2008)	**Ag**	**31.41**	38.43	0.12	5.6	0.5	1.17	4.62	0.68	0.43	0.48	0.11
	G	27.38	**26.66**	0.4	7.83	1.08	4.07	9.67	1.65	2.19	0.00	0.00
	F_r	0.60	0.35	**85.12**	9.57	12.03	0.53	12.84	20.78	2.32	0.06	0.00
	F_{um}	11.86	13.6	2.67	**43.96**	4.04	9.23	24.13	2.24	14.65	12.12	0.00
	E_f	1.22	1.78	5.56	12.5	**41.41**	15.64	10.98	38.18	12.04	5.91	0.00
	E_i	0.75	1.67	1.63	5.11	20	**21.47**	5.02	10.5	9.88	9.14	0.00
	S_{dh}	16.91	10.0	3.32	7.24	5.31	7.34	**24.79**	11.64	5.06	0.00	0.14
	B	3.99	2.15	0.9	1.44	7.88	2.55	3.82	**9.78**	1.59	2.89	0.00
	Adh	0.09	0.00	0.00	0.11	0.36	17.26	0.00	0.41	**26.05**	22.04	0.00
	Tg	0.17	1.79	0.02	5.68	6.25	20.06	0.00	2.0	25.39	**45.86**	0.00
	W	1.08	0.49	0.19	0.52	0.22	0.34	2.38	0.6	0.10	0.32	**97.66**
	No data	**4.58**	**3.11**	**0.12**	**0.46**	**0.96**	**0.37**	**1.77**	**1.59**	**0.33**	**1.19**	**2.1**
	G/L	**-46.04**	**29.23**	**1.82**	**-3.18**	**31.62**	**76.05**	**26.23**	**-59.98**	**-41.49**	**236.62**	**302.03**
	Cl.Ch	**68.59**	**73.34**	**14.89**	**56.06**	**58.59**	**78.53**	**75.22**	**2.34**	**54.14**	**90.22**	**73.96**

G/L = Gain/Loss in km^2 **Cl. Ch.** = Class change in percent

Discussion

Ecosystems are not static but exposed to a certain natural and human-induced disturbance regime that provides temporal niches for regeneration and development. In consequence, changes in disturbance regimes are likely to affect community distribution, structure, composition, diversity, and functioning (Jentsch et al. 2002). Such responses get stronger with increasing magnitude, frequency, and diversity of the disturbances. The frequency or recurrence interval of disturbance is decisive because it must fit the natural dynamics (e.g., life cycles of key species). Abiotic factors such as aspect and altitude-induced climatic variability, as well as biological and ecological factors such as competition, nutrient availability, and soil moisture, have played important roles in shaping tropical mountain vegetation over time and space (Duveiller et al. 2008; Nagy and Grabherr 2009). Besides, climatic variability that is likely to increase as a consequence of climate change (Jentsch and Beierkuhnlein 2003, 2008) will create additional stress for many organisms, especially in these already rather extreme environments.

However, recently, the most prominent changes in tropical ecosystems are related to land use and landcover change such as deforestation, land clearing for agricultural expansion, anthropogenic fire, grazing, and plantations (Hannah et al. 2002; Röder et al. 2008). In the case of the Bale Mountains, we find that the speed of change and the deviating quality of disturbances over time is reaching a higher level. As a result, the Bale Mountains are experiencing rapid and far-reaching changes in the cover and spatial pattern of ecosystems and land use types over the last decades.

Vegetation pattern and cover change

Image classification across multiple time steps enables us to assess how vegetation units, land cover and use types, or ecosystems have changed in landscapes. Such developments are a surrogate of all changes in biodiversity that are related to them (such as shifting species composition, distribution, and abundance patterns). Within a given time slice, the analysis reveals clear zonation along altitudinal gradients and as altitude increases, so does a turnover of vegetation types, resulting in compressed ecological zones. This is typical for tropical mountains (Körner 1999; MEA 2005b; Wana and Beierkuhnlein 2011) and likely facilitates high biodiversity due to species coexistence within a narrow range (Beck and Richter 2008). In the recent past, increasing areas of the Afromontane ecosystems (up to 3,200m asl) in the Bale Mountains are modified and degraded due to human activities (*see* also Amente 2005).

In the study area, we find a strong but also cover type specific transition of LULC types based on the change detection matrix. The rate of transformation differs for the reference periods. The first reference period (1973 to 1987) shows a marked transition from grassland to croplands. This period was characterized in Ethiopia by a shift in tenure policy, villagization, resettlement, and climate variability-induced droughts (Getahun 1984; Hillmann 1990). The second period (1987 to 2000) is characterized by rapid upwards expansion of agriculture, the construction of a large hydroelectric dam, and the proliferation of commercial farms and enrichment plantations. The construction of the Melka Wakena hydroelectric dam also dramatically influenced the landscape. Water bodies gain considerable area from grassland, agricultural lands, and barren areas, respectively. Such conversions from land area to water bodies have profound impacts on ecosystems such as the irreversible loss of wildlife habitats (e.g., Khan et al. 2006). Overall, during this time, in addition to agricultural expansion, there was also observed intensive deforestation, habitat simplification, and narrowing of certain cover types. During the third time step (from 2000 to 2008), the expansion of agriculture halted. The most important event during this time is the 2000 Bale fire (*see* also Wesche 2003).

Our analysis also showed that plant species at the Afroalpine zone are more homogeneous and characterized by a very limited ecological range. Historically, the Afroalpine zone of the area represented very isolated ecosystems that were less affected by human activities, except for some pastoralist and herder activities. However, recently human-induced direct and indirect threats are becoming more and more prevalent in this zone too. Impacts include increased frequency of grazing (Amente 2005), fires (Wesche et al. 2000), and prolonged droughts (Wesche 2003). Archaeological evidence suggests that areas higher than 4,000m asl have been cultivated in the past during episodes of climatic warmth (Barry and Seimon 2000). Therefore, in the future with climate warming and intensified human impacts, Afroalpine ecosystems are likely to experience significant pressure. Worst of all, these ecosystems have nowhere else to go - they are already compressed at the top of the mountain (Nogues-Bravoa et al. 2007). These vulnerable, fragile ecosystems are home to many endemic animals and plants, and thus are critically important with regard to wildlife and endemic alpine plant conservation.

The growing levels of resource exploitation in the Bale Mountains are also expected to compromise the many ecosystem services these mountains deliver to the adjacent valleys and lowlands. Historically there are various sociopolitical, socioeconomic, and socio-cultural interactions between people in highland and lowland Ethiopia. Hence, ecological instability in the highlands is likely to initiate political, economic, and cultural instability in the lowlands.

The main drivers of LULCC

Global change is expected to cause increasing declines in terrestrial biodiversity. Sala et al. (2000) identified five major drivers of terrestrial biodiversity loss. They found LULCC to be the main threat to terrestrial ecosystems, followed by climate change, nitrogen deposition, biotic exchange, and elevated carbon dioxide concentration. In mountain ecosystems impacts of these drivers will be felt at different scales and varied degrees of magnitude. Of all drivers, habitat loss and fragmentation due to LULCC in synergy with climate change will remain a paramount issue of biodiversity conservation in the twenty-first century (Lovejoy and Hannah 2005; Olson et al. 2008). In the Bale Mountains, the main agents of the observed rapid LULCC over the last 40 years refer to the following categories: rapid population growth and resettlement, agricultural expansion, deforestation and land clearing, and intensified anthropogenic fire regime.

Population growth and resettlement

Currently, the Bale Mountains are experiencing the highest population density in their history. The problem of population growth is a serious issue and has been identified as early as the 1980s (e.g., Messerli et al. 1990). However, this did little to avert the problem. For example, the population of the Bale zone has grown from 1,217,864 to 1,727,306 between 1994 and 2005 (CSA 2005). In the four subzones that surround the Bale Mountains, the population density is ~77 persons per km^2, which is three times higher than the population density within the mountain zone itself (27 persons per km^2). The population growth rate in Oromia regional state is about 2.9% per year (CSA 2007). Not surprisingly, recent settlements are encroaching into the area (Amente 2005; Senbeta and Denich 2006). Besides, the Bale region is directly affected by the post-drought resettlement and villagization programs of the 1980s and 1990s that led to the establishment of ephemeral settlements which are housing people from northern regions.

Agricultural expansion

In the Bale Mountains, the importance of crop production declines with increasing altitude, while the importance of animal husbandry increases (Gebregziabher 1988). Since the beginning of the 1980s, mechanized farming has intensified. Getahun (1984) and Hillman (1986, 1990) observed human-induced instability of ecosystems as a result. Periodically, crop cultivation, especially barley cultivation, has been encroaching on the steeper, well-drained lower areas of the Afroalpine zone up to 3,500 m asl (Hillman1986). Results from our analysis reveal the expansion of agriculture at even higher elevations. Specifically, there has been an increase in the intensity of human activities in the Afromontane area and further encroachment to the Afroalpine zone.

Taddese (2001) noted the failure of rain-fed agriculture throughout Ethiopia due to uncertainty of rainfall and increased intensity of droughts, which are resulting in massive food shortages. These phenomena exert a major influence on human land use patterns. For example, people are shifting to animal husbandry throughout eastern Africa (e.g., Galvin et al. 2001). Similarly, in Ethiopia livestock has become a means of income diversification and a drought-coping strategy. The number of livestock has increased in the Bale Mountains area with time. The recent ratio is one cattle per head (CSA 2009) and Amsalu and de Graaff (2006) reported that in 2002, the livestock reached an unprecedented density of 314 animals per km^2. In addition, increased veterinary services such as the tsetse fly eradication program are also driving higher stocking rates (Reid et al. 2000).

Intensified grazing of the Afroalpine zone is a serious ecological problem. These ecosystems are not adapted to strong herbivore pressure. Afroalpine eco-systems are likely to be irreversibly damaged by overgrazing taking ecological time scales into account because the contributing species exhibit low growth rates and rather long-life cycles (Hillmann 1990; Uhlig 1990; Buytaert et al. 2010). Traditionally, local pastoralists drive their herd to the Afroalpine area to use Horas (mineral springs) and graze the delicate Afroalpine vegetation (Hillmann 1990). Now, Afroalpine meadows are increasingly grazed throughout the year by various kinds of livestock (mainly cattle, goats, and sheep). This results in trampling damage to soils as well as in the uprooting of many types of grass and herbs, which in turn is facilitating the local extinction of palatable endemic plant species by eliminating shelter for plant seedlings (Uhlig 1990). In addition, the frequency and intensity of alpine grazing are increasing because of land degradation at lower elevations, increased pastoralist encroachment, occupation of grazing and browsing land by commercial farms, increased livestock populations, and, last but not the least, climate change-induced drought in the lowlands.

Deforestation and land clearing

Deforestation is one of the leading drivers of biodiversity loss (MEA 2005a). In the Bale Mountains, fuelwood for nearby towns and villages is sourced almost entirely from natural forests. On average one household uses about 6m^3 of wood year^1 (Amente 2005). Tree species such as *Juniperus excelsa, Podocarpus falcatus*, *Hagenia abyssinica*, and *Olea Africana* are heavily exploited. Analyzing

LULCC, we detect a slight increase in the density of woody vegetation in the upper montane forest from the change detection matrix. This can be explained by the recent introduction of enrichment plantations of eucalyptus (*Eucalyptus globulus*) and cedar (*Cupressus lusitanica*) in the peripheral areas and on former logging sites. We also observe the further intensification of coffee, fruits, and enrichment plantations across the landscape as a whole. These developments are improving vegetation cover and supporting the productivity of the region, but they are increasingly replacing the former species rich and endemic fauna and flora.

Fire

Fire was detected in all time intervals and is a common phenomenon in the area, especially at the upper and lower limits of the *Erica* forest (Wesche et al. 2000; Tesfaye et al. 2004). Fires are also frequent in the Afromontane shrubs and herbaceous formations located on the eastern slopes of the Bale Mountains next to the lowlands. Today, fires are mainly of anthropogenic origin. They are lit intentionally to clear poaching ground, improve grazing via regeneration of grasses and *Erica*, and clear the hiding places of Hyenas and other wild animals, as well as accidentally after honey gathering (Sillero-Zubiri and Macdonald 1997; Wesche et al. 2000).

Conclusion

All in all our findings reveal that the Bale Mountains are facing a strong land use and land cover change which is very likely intensified by climate change. Change detection using remote sensing data is an appropriate tool to identify regionally specific transitions (e.g., high altitude versus lowlands), habitat-specific changes (e.g., turnover in space for certain ecosystems in comparison with others), and the direction of change and the drivers (e.g., agriculture, infrastructure). Besides, such approaches are important to consolidate and supplement the traditional field research methodologies. The Bale Mountains have been considerably transformed over the last 40 years. This has endangered and is threatening the high diversity of endemic plants and animals of unique massif. The remote sensing based investigations supplemented by the different accounts on the area provide spatiotemporally resolved information on this issue. The speed of the ongoing processes clearly shows that there is a need for immediate action and intervention if the unique biodiversity of the Bale Mountains shall be preserved.

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References

Admasu, E., Thirgood, S. J., Bekele, A., & Laurenson M. K. (2004). Spatial ecology of golden jackal in farmland in the Ethiopian Highlands. African Journal of Ecology, doi:10.1111/j.1365-2028.2004.00497.x

Alphan, H., Doygun, H., & Unlukaplan, Y. I. (2009). Post-classification comparison of land cover using multitemporal Landsat and ASTER imagery: the case of Kahramanmaraş, Turkey. Environmental monitoring and assessment, doi:10.1007/s10661-008-0274-x

Amente, G. (2005). Rehabilitation and sustainable use of degraded community forests in the Bale mountains of Ethiopia. Inaugural Dissertation. Faculty of Forest and Environmental Sciences, Albert-Ludwigs-University, Freiburg, Germany.

Amsalu, A., & de Graaff, J. (2006). Farmers views of soil erosion problems and their conservation knowledge at Beressa watershed, central highlands of Ethiopia. Agriculture and Human Values, doi:10.1007/s10460-005-5872-4

Atkinson, P. M., Foody, G. M., Gething, P. W., Mathur, A., & Kelly, C. K. (2007). Investigating spatial structure in specific tree species in ancient semi-natural woodland using remote sensing and marked point pattern analysis. Ecography, 30, 88-104. doi:10.1111/j.0906-7590.2007.04726.x

Barry, R. G., & Seimon, A. (2000). Research for mountain area development: Climatic fluctuations in the mountains of the Americas and their significance. Ambio, 29 (7), 364-370, doi:10.1579/0044-7447-29.7.364

Beck, E., & Richter, M. (2008). Ecological aspects of a biodiversity hotspot in the Andes of southern Ecuador. In S. R. Gradstein, J. Homeier & D. Gansert (Eds.), The Tropical Mountain Forest patterns and processes in a biodiversity hotspot. Biodiversity and Ecology Series, 2, 7-24.

Bonnefille, R. (1983). Evidence for a cooler and drier climate in the Ethiopian uplands towards 2.5 Mys ago. Nature, doi:10.1038/303487a0

Buytaert, W., Cuesta-Camacho, F., & Tobon, C. (2010). Potential impacts of climate change on the environmental services of humid tropical alpine regions. Global Ecology and Biogeography, doi:10.1111/j.1466-8238.2010.00585.x

Chiarucci, A., Araujo, M. B., Decocy, G., Beierkuhnlein, C., & Fernandez-Palacios, J. M. (2010). The concept of potential natural vegetation: an epitaph? Journal of Vegetation Science, doi:10.1111/j.1654-1103.2010.01218.x

CSA. (2005). Population sample survey. Volume I. Addis Ababa: Federal Democratic Republic of Ethiopia Central Statistical Agency.

CSA. (2007). Statistical abstract 2007. Volume I. Addis Ababa: Federal Democratic Republic of Ethiopia Central Statistical Agency.

CSA. (2009). Agricultural sample survey. Volume I. Addis Ababa: Federal Democratic Republic of Ethiopia Central Statistical Agency.

Darbyshire, I., Lamb, H., & Umer, M. (2003). Forest clearance and regrowth in northern Ethiopia during the last 3000 years. The Holocene, doi:10.1191/0959683603hl644rp.

Duveiller, G., Defourny, P., Descle'e, B., & Mayaux, P. (2008). Deforestation in Central Africa: Estimates at regional, national and landscape levels by advanced processing of systematically distributed Landsat extracts. Remote Sensing of Environment, doi:10.1016/j.rse.2007.07.026

Elmore, A.J., Mustard, J.F., Manning, S.J., & Lobell, D.B. (2000). Quantifying vegetation change in semiarid environments: Precision and accuracy of spectral mixture analysis and the normalized difference vegetation index. Remote Sensing of Env., doi:10.1016/S0034-4257(00)00100-0

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N., & Snyder, P. K. (2005). Global consequences of land use. Science, doi:10.1126/science. 1111772

Foody, G. M. (2002). Status of land cover classification accuracy assessment. Remote Sensing of Environment, doi:10.1016/S0034-4257(01)00295-4

Friis, I. (1992). Forests and forest trees of northeast tropical Africa. Their natural habitats and distribution patterns in Ethiopia, Djibouti and Somalia. Kew Bull Additional Series 15, HMSO, London.

Galvin, K. A., Boone, R. B., Smith, N. M., & Lynn, S. J. (2001). Impacts of climate variability on East African pastoralists: linking social science and remote sensing. Climate Research, doi:10.3354/cr019161

Gebregziabher, T. (1988). Vegetation and environment of the mountains of Ethiopia: Implications for utilization and conservation. Mountain Research and Development, 8(2/3), 211-216.

Gebregziabher, T. (1991). Management of mountain environments and genetic erosion in tropical mountain systems: The Ethiopian Example. Mountain Research and Development, 11(3), 225-230.

Getahun, A. (1984). Stability and instability of mountain ecosystems in Ethiopia. Mountain Research and Development, 4(1), 39-44.

Grepperud, S. (1996). Population pressure and land degradation: The case of Ethiopia. Journal of Environmental Economics and Management, doi:10.1006/jeem.1996.0002

Hagedorn, F., Mulder, J., & Jandl, R. (2010). Mountain soils under a changing climate and land-use. Biogeochemistry, doi:10.1007/s10533-009-9386-9

Hannah, L., Midgley, G. F., & Miller, D. (2002). Climate change-integrated conservation strategies. Global Ecology and Biogeography, doi:10.1046/j.1466-822X.2002.00306.x

Hedberg, O. (1964). Feature of Afroalpine plant ecology. Uppsala: Almquist & Wiksells Boktryckeri

Hillman, J. C. (1986). Conservation in Ethiopia's Bale Mountains. Endangered Species, 3, 1-4.

Hillman, J. C. (1988). The Bale Mountains National Park area, southeast Ethiopia, and its management. Mountain Research and Development, 8(2/3), 253-258.

Hillmann, J. C. (1990). The Bale Mountains National Park area, southeastern Ethiopia, and its management. In B. Messerli & H. Hurni (Eds.), African Mountains and Highlands: Problems and Perspectives (pp. 277-286). Missouri, Walsworth Press: The African Mountain Association (AMA).

Jensen, R. J. (2007). Remote Sensing of the Environment. An Earth Resource Perspective. 2nd Edition. Pearson Prentice Hall. Upper Saddle River NJ.

Jentsch, A., & Beierkuhnlein, C. (2003). Global climate change and local disturbance regimes as interacting drivers for shifting altitudinal vegetation patterns. Erdkunde, 57, 216-231.

Jentsch, A., & Beierkuhnlein, C. (2008). Research frontiers in climate change: Effects of extreme meteorological events on ecosystems, CR Geoscience, 340, 621-628, doi:10.1016/j.crte.2008.07.002

Khan, S., Tariq, R., Yuanlai, C., & Blackwell, J. (2006). Can irrigation be sustainable? Agricultural Water Management, doi:10.1016/j.agwat.2005.07.006

Körner, C. (1999) Alpine Plant Life. Springer Verlag, Berlin.

Kreyling, J., Wana, D., & Beierkuhnlein, C. (2010). Potential consequences of climate warming for tropical plant species in high mountains of southern Ethiopia. Diversity and Distributions, doi:10.1111/j.1472-4642.2010.00675.x

Laurenson, K., Sillero-Zubiri, C., Thompson, H., Shiferaw, F., Thirgood, S., & Malcolm, J. (1998). Disease as a threat to endangered species: Ethiopian wolves, domestic dogs and canine pathogens. Animal Conservation, doi:10.1111/j.1469-1795.1998.tb00038.x

Lovejoy, T. E., & Hannah, L. (2005). Climate Change and Biodiversity. Yale University Press. New Haven. USA.

Lu, D., Mausel, P., Brondizio, E., & Moran, E. (2004). Change detection techniques: A review. International Journal of Remote Sensing, doi:10.1080/0143116031000139863

Messerli, B., Hurni, H., Woldesemait, B., Tedla, S., Ives, J. D., & Woldemariam, M. (1990). African mountains and highlands: An introduction. In B. Messerli & H. Hurni (Eds.), African Mountains and Highlands: Problems and Perspectives (pp. 7-15). Missouri, Walsworth Press: The African Mountain Association (AMA).

Miehe, G. & Miehe, S. (1994). Ericaceous Forests and Heathlands in the Bale Mountains of South Ethiopia: Ecology and Man's Impact. Stiftung Walderhaltung in Afrika, Hamburg.

Millennium Ecosystem Assessment (MEA). (2005a). Ecosystems and Human Well-being: Biodiversity Synthesis. World Resources Institute, Washington, DC.

Millennium Ecosystem Assessment (MEA). (2005b). Status and trends in mountain systems. World Resources Institute, Washington, DC.

Mohamed-Saleem, M. A., & Woldu, Z. (2002) Land use and biodiversity in the upland pastures in Ethiopia. In C. Körner & E. M. Spehn (Eds.), Mountain Biodiversity: a Global Assessment (pp. 277-282). Midsomer Norton: The Parthenon Publishing Group.

Nagy, L., & Grabherr, G. (2009). The Biology of Alpine Habitats. Oxford University Press, Oxford.

National Biodiversity Strategy and Action Plan (NBSAP). (2005). Democratic Republic of Ethiopia. Institute of Biodiversity Conservation. Addis Ababa. Ethiopia. http://www.cbd.int/doc/world/et/et-nbsap-01-en.pdf. Accessed 20 March 2010.

Nogues-Bravoa, D., Araujo, M. B., Erread, M. P., & Martınez-Rica, J. P. (2007). Exposure of global mountain systems to climate warming during the 21st century. Global Environmental Change, doi:10.1016/j.gloenvcha.2006.11.007

Olson, J. M., Alagarswamy, G., Andresen, J. A., Campbell, D. J., Davis, A. Y., Ge, J. et al. (2008). Integrating diverse methods to understand climate-land interactions in East Africa. Geoforum, doi:10.1016/j.geoforum.2007.03.011

Osmaston, H. A., Mitchell, W. A., & Osmaston, J. A. N. (2005). Quaternary glaciation of the Bale Mountains, Ethiopia. Journal of Quaternary Science, doi:10.1002/jqs.931

Reid, R. S., Kruska, R. L., Muthui, N., Taye, A., Wotton, S., Wilson, C. J., & Mulatu, W. (2000). Land-use and land-cover dynamics in response to changes in climatic, biological and socio-political forces: the case of southwestern Ethiopia. Landscape Ecology, doi:10.1023/A:1008177712995

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F. et al. (2009). A safe operating space for humanity. Nature, doi:10.1038/461472a

Röder, A., Stellmes, M., Hill, J., Kuemmerle, T., & Tsiourlis, G. M. (2008). Analysing land cover change using time series analysis of Landsat data and geoinformation processing. A natural experiment in Northern Greece. Remote Sensing for Agriculture, Ecosystems, and Hydrology 10: Proceedings of SPIE: International Society for Optics and Photonics 7104, 710409, doi:10.1117/12.800265

Sala, O. E., Chapin, F. S., Armesto, J. J., Berlow, E., Bloompeld, J., Dirzo, R. et al. (2000). Global biodiversity scenarios for the year 2100. Science, doi:10.1126/science.287.5459.1770

Senbeta, F., & Denich, M. (2006). Effects of wild coffee management on species diversity in the afromontane rainforests of Ethiopia. Forest Ecology and Management, doi:10.1016/j.foreco.2006.05.064

Sillero-Zubiri, C., & Macdonald, D. W. (1997). The Ethiopian Wolf: Status Survey and Conservation Action plan. IUCN Canid Specialist Group, Gland, Switzerland and Cambridge, UK.

Stephens, P. A., d'Sa, C. A., Sillero-Zubiri, C., & Leader-Williams, N. (2001). Impact of livestock and Settlement on the large mammalian wildlife of Bale Mountains National Park, Southern Ethiopia. Biological Conservation, 100, 307-322. doi:10.1016/S0006-3207(01)00035-0

Taddese, G. (2001). Land degradation: A challenge to Ethiopia. Environmental Management, doi:10.1007/s002670010190

Tesfaye, G., Teketay, D., Assefa, Y., & Fetene, M. (2004). The impact of fire on the soil seed bank and regeneration of Harenna Forest, Southeastern Ethiopia. Mountain Research and Development, doi:10.1659/0276-4741(2004)024[0354:TIOFOT]2.0.CO;2

Turner, B. L., Lambin, E. F., & Reenberg A. (2007). The emergence of land change science for global environmental change and sustainability. PNAS, doi:10.1073/pnas.0704119104

Uhlig, S. K., & Uhlig, K. (1991). Mountain chronicles. Studies on the altitudinal zonation of forests and alpine plants in the central Bale Mountains, Ethiopia. Mountain Research and Development, 11(2), 153-256.

Uhlig, S. K. (1990). Mountain forests and the upper tree limit on the Southeastern plateau of Ethiopia. In B. Messerli & H. Hurni (Eds.), African Mountains and Highlands: Problems and Perspectives (pp. 237-248). Missouri, Walsworth Press: The African Mountain Association (AMA).

United States Geological Survey (USGS) 2009. Landsat Archieve. Landsat standard data products. http://landsat.usgs.gov. Accessed 20 Sept 2010.

Umer, M., Lamb, H. F., Bonnefille, R., Lezine, A. M., Tiercelin, J. J., Gibert, E., Cazet, J. P., & Watrin, J. (2007). Late Pleistocene and Holocene vegetation history of the Bale Mountains, Ethiopia. Quaternary Science Review, doi:10.1016/j.quascirev.2007.05.004

Wana, D., & Beierkuhnlein, C. (2011). Responses of plant functional types to environmental gradients in the south-west Ethiopian highlands. Journal of Tropical Ecology, 27, 289-304 doi:10.1017/S0266467410000799

Wesche, K. (2003). The importance of occasional droughts for afroalpine landscape ecology. Journal of Tropical Ecology, 19, 197-208. doi:10.1017/S0266467403003225

Wesche, K., Miehe, G., & Kaeppeli, M. (2000). The significance of fire for Afroalpine ericaceous vegetation. Mountain Research and Development, doi:10.1659/0276-4741(2000)020[0340:TSOFFA]2.0.CO;2

Wickware, G. M., & Howarth, P. J. (1981). Change detection in the Peace-Athabasca Delta Using Digital Landsat Data. Remote sensing of environment, doi:10.1016/0034-4257(81)90003-1

Woldemariam, M. (1990). An assessment of stress and strain on the Ethiopian highlands. In B. Messerli & H. Hurni (Eds.), African Mountains and Highlands: Problems and Perspectives (pp. 289-297). Missouri, Walsworth Press: The African Mountain Association (AMA).

Woldu, Z., Feoli, E., & Nigatu, L. (1989). Partitioning an elevation gradient of vegetation from south-eastern Ethiopia by probabilistic methods. Vegetatio, doi:10.1007/BF00045524

Yimer, F., Messing I., Ledin S., & Abdelkadir A. (2008). Effects of different land use types on infltration capacity in a catchment in the highlands of Ethiopia. Soil Use and Management, doi:10.1111/j.1475-2743.2008.00182.x

Chapter 2

Ericaceous vegetation of the Bale Mountains of Ethiopia will prevail in the face of climate change

Yohannes O Kidane*[1], Samuel Hoffmann[1], Anja Jaeschke[1], Mirela Beloiu[1,4], Carl Beierkuhnlein [1,2,3]

[1] Department of Biogeography, Bayreuth, University of Bayreuth, Germany
[2] Bayreuth Center of Ecology and Environmental Research (BayCEER), Bayreuth, Germany
[3] Geographical Institute Bayreuth (GIB), Bayreuth, Germany
[4] Institute of Terrestrial Ecosystems, Department of Environmental System Sciences, ETH Zurich, Zurich, Switzerland

*** Corresponding Author**

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Abstract

Climate change impacts the structure, functioning, and distribution of species and ecosystems. It will shift ecosystem boundaries, potentially affecting vulnerable ecosystems, such as tropical Africa's high mountain ecosystems, i.e., Afroalpine ecosystems, and their highly susceptible uniquely adapted species. However, ecosystems along these mountains are not expected to respond similarly to the change. The ericaceous woody vegetation, located between the low-elevation Broadleaf Forests and high-elevation Afroalpine vegetation, is anticipated to be affected differently. We hypothesize that projected climate change will result in an upward expansion and increasing dominance of ericaceous vegetation, which will negatively impact the endemic rich Afroalpine ecosystems of the extensive Sanetti plateau. Hence, we modeled the impact of future climate change on the distribution of ericaceous vegetation and discussed its effect on bordering ecosystems in the Bale Mountains. We applied four familiar correlative modeling methods: Bioclim, Domain, Generalized Linear Methods (GLMs), and Support Vector Machines (SVMs). We used WorldClim's bioclimatic variables as environmental predictors and two representative concentration pathways (RCPs) of the IPCC Fifth Assessment Report (AR5) climate change scenarios, namely RCP4.5 and RCP8.5 for future climate projection. The results indicate increased ericaceous vegetation cover on the midaltitude of northwestern, northern parts of the massif, and the Sanetti plateau. We observed upward range expansion and increased of close ericaceous vegetation in mid altitudes while receding from the lower range across the massif. Moreover, the current ericaceous vegetation range correlates to the temperature and precipitation trends, reaffirming the critical role of temperature and precipitation in determining species distributions along elevational. The results indicate the high likelihood of considerable changes in this biodiversity hotspot in Eastern Africa.

Keywords: Species distribution model, ericaceous, biodiversity, vegetation dynamics, ensemble model, high mountains, tree line, Ethiopia, endemism

1. Introduction

The recent climate change-induced warming is the most pervasive of the various threats to the planet's biodiversity [10, 37, 43]. Therefore, an urgent challenge in biogeography and ecology is determining how species and ecosystems respond to climate changes [19]. The recently observed climate change across tropical regions is significantly higher than the global average; for example, there are observed temperature increases for the tropical rainforest regions at a mean rate of 0.26 +/- 0.05 °C per decade, with an intensification during the El Niño events [44]. Three out of the four of the IPCC Fifth Assessment Report (AR5) Representative Concentration Pathways (RCPs) predicted moderate to severe climate warming throughout the coming century in response to changes in radiative forcing arising from anthropogenic emissions of greenhouse gases and aerosols [32]. Therefore, climate change will likely induce thermal isotherm shifts, disrupting the stability of Afroalpine mountain ecosystems and affecting the unique plant diversity, leading to unexpected taxonomic and functional reorganization of communities and massive extinctions of endemic species [10, 42, 43].

Mountains are complex landforms that uniquely contribute to biodiversity. Hence, are important in investigating climate change's impact on individual species and ecosystems. They modify regional macroclimates and are endowed with complex microclimatic regimes. The steep gradients of temperature and precipitation and topographic complexity within mountains result in many microsites with a range of adjacent thermal niches [3, 40, 47]. In general, there are two categories of environmental changes with altitude: those physically tied to meters above sea level (m asl), such as atmospheric pressure, temperature, and clear-sky turbidity; and those that are not generally altitude specific, such as moisture, hours of sunshine, wind, season length, geology, and even human land use [40]. Here, we modeled the significance of the temperature and moisture-related bioclimatic variables for the diversity and distribution of ericaceous vegetation and its implication for the extensive Afroalpine ecosystems.

The spatial isolation of mountains over a long period has supported the evolution of many endemics [16, 60, 62]. Tropical alpine ecosystems above the treeline are particularly isolated and consequently host highly adapted endemic species sensitive to climate change [7, 23, 49, 57, 70]. Tropical African high mountain ecosystems, i.e., Afroalpine ecosystems, occur in isolated patches restricted to peaks of the high mountains along the Great Rift Valley and Cameron-Nigeria Mountain ranges between Tropic of Capricorn and Tropic of Cancer [25,18]. These spectacular ecosystems are habitats for unique plants with specific morphological and functional adaptations that exhibit distinctive traits and distinctive adaptations to diurnal freeze-thaw cycles [24, 31]. The Afroalpine plant species have long life cycles reflected in woody structures, above and belowground longevity, and limited dispersal capacity resulting in inertia at the ecosystem level [57]. Hence, the rapid range shift of species and ecosystems or local adaptation to novel environmental conditions along mountains is likely to happen by plants with broad phenotypic plasticity and higher dispersal ability.

The Bale Mountains form an enormous contagious massif of extensive plateaus above 3400 m asl in Africa, supporting the extensive *ericaceous* vegetation [48]. The ericaceous vegetation is a vital component at the transition between Broadleaf Forests and Afroalpine vegetation. It has a broad distribution range, high thermal tolerance, dispersal ability (wind dispersal), and adaptation potential. Key members of this vegetation type may outcompete some exclusively Afroalpine plants in case of upward shift [18]. One-third of the Afroalpine flora is solely limited to the alpine zone. At the same time, several members of this group of plants have a broader range of distribution that extends to lower vegetation belts, such as the ericaceous vegetation [39].

The term "ericaceous" describes a plant functional type with needle-leaved foliage and a taxonomic group of plants belonging to the family Ericaceae. The genus *Erica* comprises acidophilous woody plants [73, 46]. In the Bale Mountains, the "Ericaceous Belt" range extends between 3100 m and 4200 m asl and is dominated by *E. arborea* L. and *E. trimera* (Engl.) Beentje [24, 48] (Hence forth *Erica*). The Ericaceous Belt is a resilient ecosystem that serves as a firetrap that promotes and perpetuates the system's stability [20]. *Erica* leaf shedding builds good surface fuels relatively quickly and stimulates the Ericaceous Belt's fire risk cycle [21, 34, 36, 73,75]. However, the traditional fire management system has maintained biodiversity by creating vegetation mosaics, with young, non-flammable stands acting as fuel breaks [34, 36]. Besides, soft *Erica* shoots are often grazed and browsed by domestic stock, and the fire-killed *Erica* stumps are collected for firewood by locals.

Most recent SDMs focus on extinction risks of species or groups rare and under threat of extinction, keystone species, or functional types [68]. Little is known about the potential range retraction, expansion, or extinction of the widespread species of the remote landscape such as *Erica*, which are critically important to local ecosystems and biodiversity conservation management. Even slight declines in such species can significantly affect ecosystem structure, function, and services [71]. To date, the extent of *Erica*'s current distribution range and suitable habitat, the impacts of projected climate change in determining its distribution, and the main bioclimatic factors that control its expansion and distribution are not well studied in the Bale Mountains. Relatively, the role of fire, land use, plant diversity distribution, and herbivory as central players in *Erica* dynamics are more researched [e.g., 20, 21, 30, 31, 34, 35, 36, 48, 53, 64, 65, 73, 74, 75].

In addition, the Bale Mountain massif and surrounding lowlands, similar to other parts of East Africa [11], are inhabited by hundreds of thousands of poor small-scale subsistence farmers. [52] reviewed the last sixty years' anthropogenic temperature increase across east tropical Africa and estimated it has increased from 0.278^0C to 0.72^0C per decade. [33] estimated approximately 1.0°C of global average above pre-industrial levels, likely ranging from 0.8°C to 1.2°C. Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate [33]. Hence, information from reliable species distribution models (SDMs) enables science to build a basic understanding of ecosystem response and policy to plan reliable mitigation and adaptation measures.

SDMs are especially suited to assess species and ecosystem status in overbroad, remote, and inaccessible areas such as mountain ecosystems [42]. Therefore, they are critical to fundamental and applied research in biogeography [1]. We applied SDMs to predict projected *Erica* distribution using WorldClim's [28] bioclimatic variables as environmental predictors and two representative concentration pathways (RCPs) of IPCC Fifth Assessment Report (AR5) climate change scenarios, namely RCP4.5 and RCP8.5 for future climate projection. RCP4.5 is the intermediate scenario with emissions peak around 2040, and RCP8.5 is a projection with very high Green House gas (GHG) emissions that assume emissions continue to rise throughout the 21st century. Scenario selection was based on the notion that climate change is happening and partial damage has already occurred. The emission will persist through the first half of the 21st century and is anticipated to continue to cause changes in the climate, biological and other systems [33].

Considering the severity of the anticipated climate change, we asked whether the future environmental conditions would favor further expansion and dominance of plants with a broader habitat range, such as the ericaceous vegetation. We hypothesize that projected climate change will result in an upward expansion and increasing dominance of ericaceous vegetation, which will negatively impact the endemic rich Afroalpine ecosystems of the extensive Sanetti plateau. We further hypothesize that due to its broad phenotypic plasticity, the ericaceous vegetation will respond to the changes and prevail in the area of its potential suitable habitat.

In general, the role of climate change in determining *Erica's* distribution and its implication for associated alpine and subalpine flora is lacking. Understanding its current and future distribution and ecological range in the face of climate change contributes to biodiversity conservation management planning, climate change adaptation and mitigation strategies, and the development of sound local management strategies. Hence, this research aims to model the current *Erica* distribution range under current bioclimatic conditions and projected climate change. Specifically, the goals are to model the current distribution of *Erica*, identify the main bioclimatic variables that control Erica's distribution, model its future potential distribution range*,* and discuss the implication for the Afroalpine vegetation.

2. Materials and Methods

2.1 Study Area

2.1.1 Location and Geology

The study was carried out in the Bale Mountains of Southeastern Ethiopian highlands focusing on the ericaceous vegetation of the massif within an area of geographic extent 39°25′E, 40°00′E and 06°25′S, 07°10′N (**Figure 1**). The massif is home to the most extensive Afroalpine ecosystems in Africa. They were once extensively glaciated, and the entire climate was much colder and drier during the glacial periods of the Pleistocene, which shaped their recent geomorphology [4, 53]. The mountains are fragmented by numerous volcanic plugs, peaks, alpine lakes, and rushing mountain streams that descend into deep rocky gorges. The mountains, especially the Afroalpine proper and ericaceous Belt, were pushed down by ~1000m and covered larger areas than today during a long period in the Pleistocene [5, 20, 22, 53]. These species assemblages are spatially condensed today.

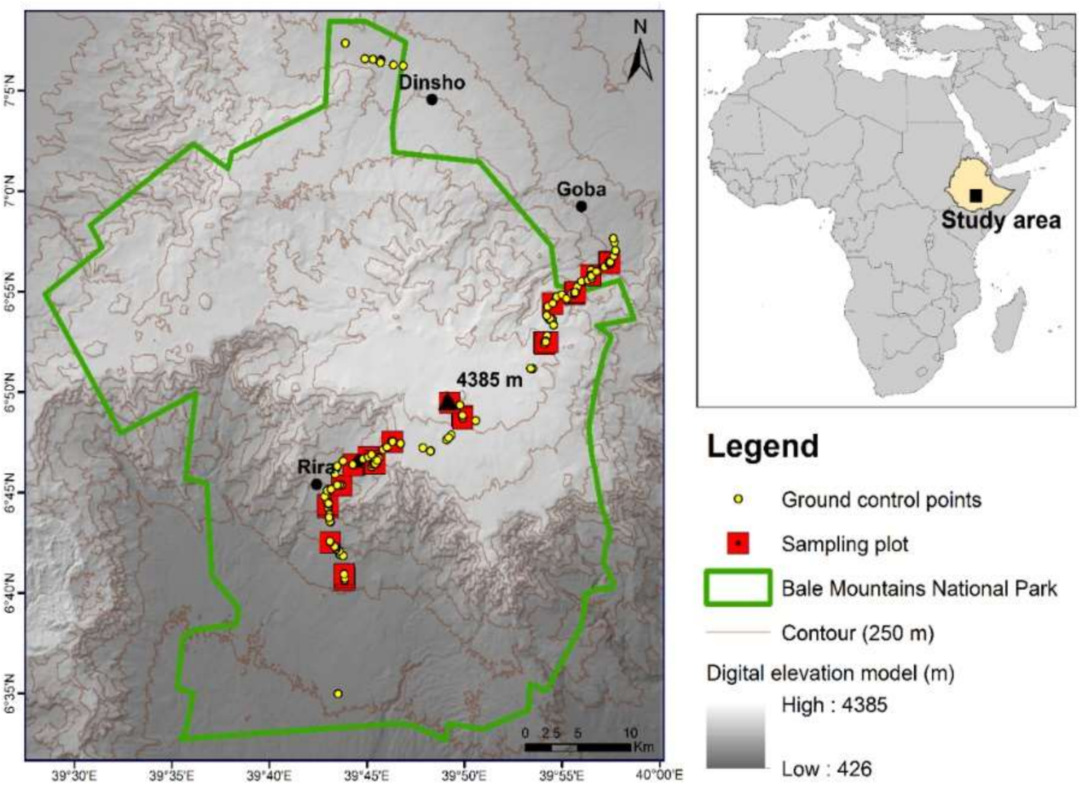


Figure 1. Map of the study area, including the transect sampling plots' location, ground controlling points, and the Bale Mountain National Park (BMNP) boundaries (Prepared by: Mirela Beloiu and Yohannes O Kidane using QGIS 3.4. [55] and Digital Elevation Model acquired from the United States Geological Survey (USGS) [66].

2.1.2 Climate

The Bale Mountains are located at the convergence of the wet East African and dry northeast African mountains of southeast Ethiopia. Rain comes to the mountains from two different sources, the equatorial westerlies (rainfall pattern influenced by the Intertropical Convergence Zone (ITCZ)) and the Indian Ocean Monsoon [64]. The south and southwest slopes are more humid with a subtropical climate and high annual rainfall up to 1500 mm/year. The north and northeastern parts experience an annual rainfall from 800 to 1100 mm and a wet season from June to September. Along Harenna escarpments, precipitation increases to around 3800 m asl, then decrease toward the summits [30].

The Afroalpine region above 3400 m asl to the summit [48] is often covered with clouds and gains less precipitation than the Afromontane range 1500 m asl to around 3250 m asl [39, 65]. In general, the Afroalpine climate is cold and wet, except in the short dry season, usually lasting from December to January or into March–April during drought years [48]. Unlike the wet season, the dry season has relatively higher daytime maximum temperatures and lower nighttime minimum temperatures in the tropical alpine zone [25]. Diurnal freeze-thaw cycles, yet slight seasonal variations in temperature, are typical in the alpine zone [24, 31]. This "summer every day, winter every night" pattern is characteristic of tropical alpine areas [25, 59]. [30] recorded an extreme diurnal temperature range of about 40 °C (-15 °C to + 26 °C) during the dry season.

2.1.3 The Ericaceous Belt

The Bale Mountains exhibit a steep gradient of ecological zones ranging from tropical rainforests to Afroalpine vegetation [38, 39]. The area above the upper montane forest, above 3100 m asl, is dominated by *E. arborea* and *E. trimera,* otherwise known as "the Ericaceous Belt" [24, 48]. The two closely related *Erica* species*, Erica arborea* L. and *Erica trimera* (Engl.) Beentje dominates this ecosystem [24, 48]. Both species have similar morphology, distribution, and habitat ecology, making it difficult to distinguish the two species in the field [21]. *E. arborea* is widely distributed in Africa, the Middle East, and Europe. At the same time, *E. trimera* is endemic to the Afroalpine mountains and occurs in several mountain systems of East Africa and the Ethiopian Highlands [48]. *E. trimera* tends to dominate at higher elevations between 3700 m asl to 4150 m asl, while *E. arborea* has a broader distribution range that extends between 3100 m and 4200 m asl [26, 48], usually extending 1000 to 1100 m vertical distance.

Erica displays different phenotypes across elevational gradients (**Figure 2**), mainly driven by environmental factors such as temperature and moisture [21,35, 48]. It appears as evergreen dwarf shrubs of a few centimeters high to trees up to 12 m [21, 48]. This older *Erica f*orest has dense multi-stem trees covered with prominent epiphytes such as mosses and ferns. Above the old growth is the mid-altitude of *Erica* distribution, the dense shrubland covered with shrubs of approximately 0.5 m to 3 m. Here, in between the resprouting *Erica* shrubs are distinct grasses and herbs growing. Finally, it occurs as a few centimeter-high shrubs at a higher elevation.

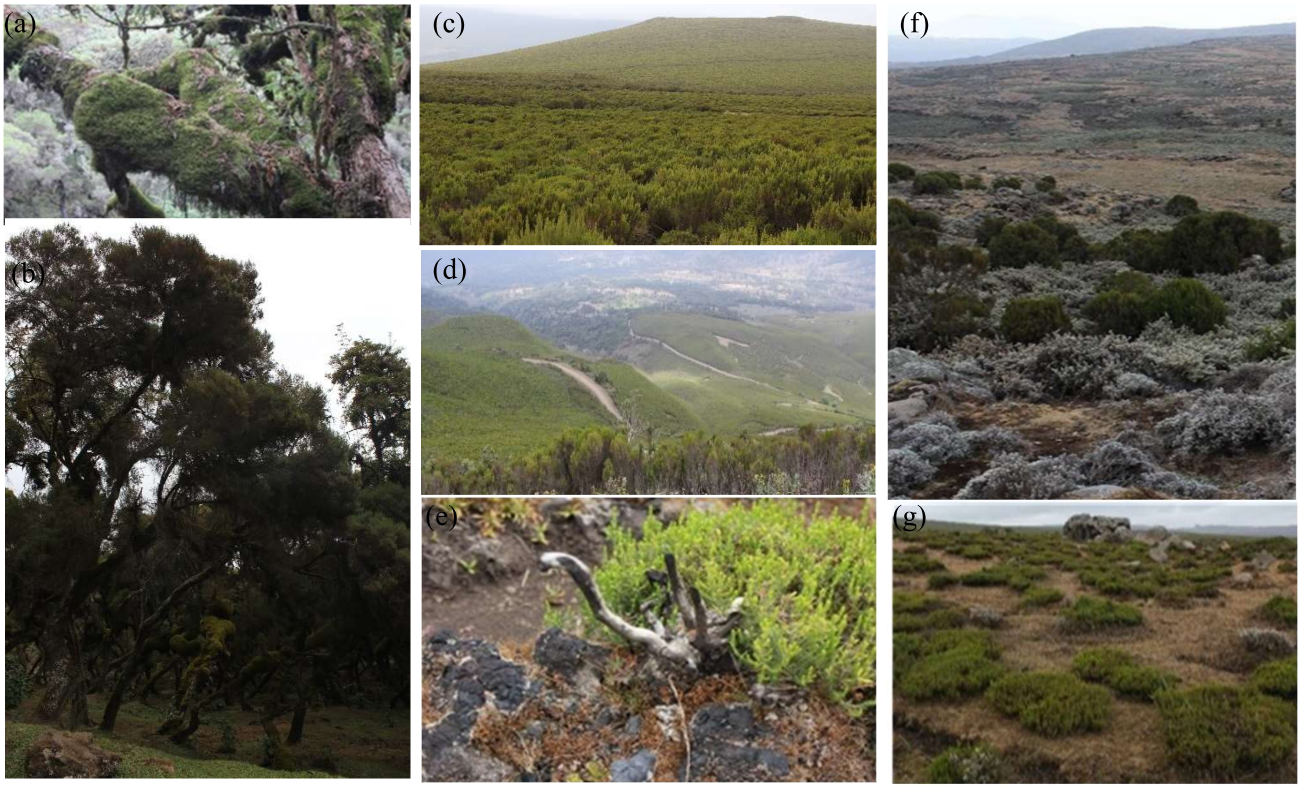


Figure 2. *Erica* succession and distribution patterns along the Bale Mountains. a and b) Old Erica tree stands up to 12 m high with thick *Breutelia spp.* Moss on the stem, c and d) Ericaceous Belt: young Erica brush 1 to 5 years old (1m to 3m high), e) *Erica* lignotubers regeneration after a fire event, and f and g) Isolated *Erica* groves at the *Erica Afroalpine* grassland ecotone mainly dominated by isolated *Erica* shrubs and different grasses.

The Senetti Plateau covers areas that start at above 3400 m asl, the alpine treeline, to the summits. The slopes are covered with lower-statured heather that merges and diffuses into Afroalpine vegetation. Here, *Erica* is kept in a shrubby state up to around 4200 m asl through repeated burning, freezing temperature, rodent disturbance, and grazing [21, 48].

On the Senetti Plateau, the plants are composed of low-statured, Tussock grass, perennial life forms, and giant rosettes, e.g., low-stature woody shrubs, herbaceous forbs, graminoids, cushions with the relative abundance of each related to their location within the massif and local microclimate. Plants like *Dipsacus pinnatifidus* Steud. ex A. Rich*.*, *Eriocaulon schimperi* Körn. ex Ruhland, *Carex monostachya* A. Rich., *Helichrysum splendens* Sims*, Helichrysum citrispinum* Delile.*, Helichrysum cymosum* (L.) D. DON., *Geranium kilimandscharicum* Engl.*, Alchemilla abyssinica* Fresen., *Alchemilla rothii* Oliv., *Artemisia afra* Jacq. ex Willd. and *Polygonum afromontanum* Greenway are common. The spectacular uniquely adopted *Rosette,* such as *Lobelia scebelii* Chiov. *Lobelia giberroa* Hemsl, and *Scenecio spp.,* are the most prominent and common plant species. Other significant plant communities such as Tussock grass-like *Pentaschistis minor* Ballard and Hubbard and *Festuca abyssinica* Hochst are common on the Afroalpine plateau.

2.2 Data Collection

2.2.1 Ground Controlling Points Collection and Data Preparation

Landsat TM+8 remote sensing images 30 m x 30 m resolution from March 8, 2017, paths 167 and 168, and raw 55 and 56 were acquired from the United States Geological Survey homepage [66]. The data preparation and modeling steps are described in **Fig. 3.** Ground control points were collected from the vegetation sampling plots and GPS recordings collected across the Bale massif during our field visit in March 2011. We used the ground control points to identify the cover classes and classification accuracy assessment. Besides, high-resolution Google Earth images and pictures (https://earth.google.com) were used to crosscheck any recent vegetation cover changes during the image classification. The altitude and coordinates of each sampling plot were recorded using Garmin GPS 3.1.

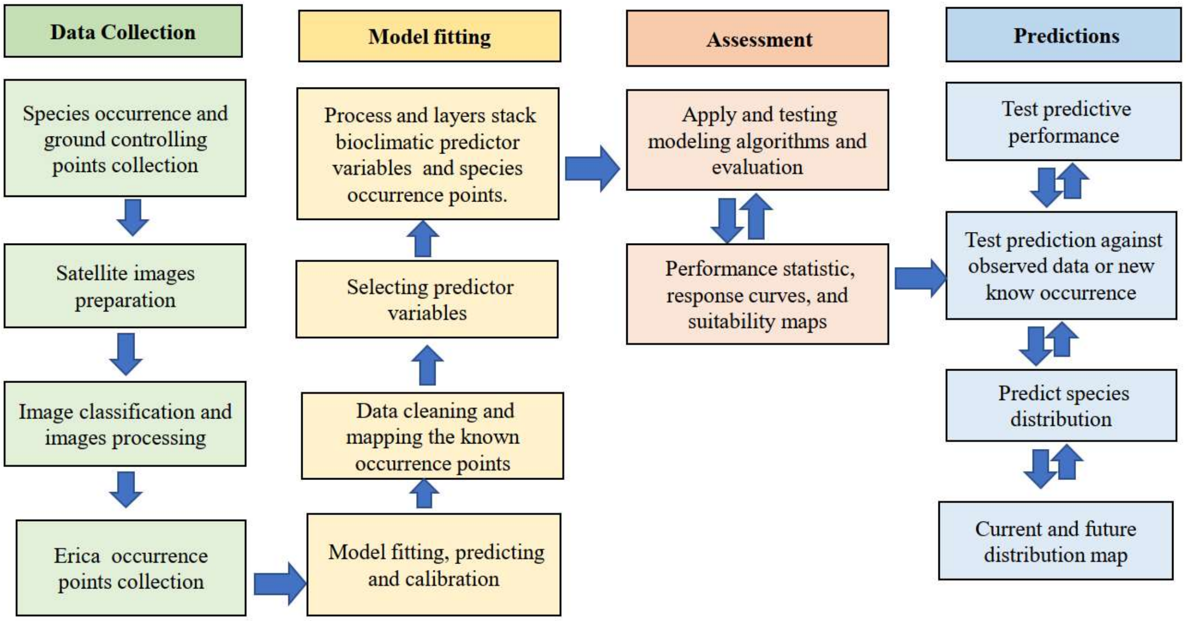


Figure 3: Modeling flow diagram detailing the main data collection and preparation steps, modeling fitting, assessment and evaluation, and prediction and validating steps.

2.2.2 Image Classification and Occurrence Data Collection

Georeferencing, image classification, occurrence points extraction, and coordinates crosschecking were carried out using QGIS 3.4 [55]. We applied the QGIS Semi-Automatic Classification image processing approach. The object-based supervised maximum likelihood algorithm was used to classify the images. In such an approach, the analyst defines areas where the landcover is known and pre-defines the Land Use Land Cover (LULC) types and the number of classes based on selected parameters [17, 72]. This approach enhances the delineation objectivity, interpretation repeatability, and processing efficiency [13].

We classified the images based on the area's known eight major vegetation classes [39]. The classification accuracy was evaluated using the kappa coefficient [58]. We achieved an overall accuracy of 93%. Usually, the image classification Kappa coefficient and overall accuracy above 73% are acceptable and required [17].

After the final classification, the landcover classes other than *Erica* were masked, and occurrence points were extracted. More than 3220 *Erica* occurrence points were collected from the final known *Erica* cover class. The modeling, including further data preparation, cleaning, and calibration was carried out using R version 3.6.0 [56] based on the SDMs steps described in Hijmans and Elith (2017) (See supplementary material). Duplicate *Erica's* occurrence points were removed from the database during the modeling proceedings. Error-free and adequately representing occurrence points were compiled and used for modeling.

2.2.3 Predictor Variables Selection and Preparation

Model outputs are primarily driven by the choice of predictor variables fitted into the models and the type and level of adjustment between the response and predictor variables [1, 50, 51]. We used the bioclimatic variables derived from the monthly temperature and rainfall values provided by WorldClim version 1.4 [28] as our main environmental predictors. We downloaded the historical (current) climate data for 1970-2000 and future 2050s (projected climate data for 2046–2065) and 2070s (projected climate data for 2081-2100) of 19 bioclimatic predictors variables at 30arc sec (~1 km^2) spatial resolution.

We selected two IPCC Fifth Assessment Report (AR5) climate change scenarios, Representative Concentration Pathways (RCPs) [33] of the Coupled Model Intercomparison Project Phase 5 (CMIP5), which were derived from the output of coupled atmosphere-ocean general circulation models (AOGCMs) [77]. We used RCP4.5 (2050s) and RCP8.5 (2070s). RCP4.5 is an intermediate scenario or likelihood that climate change will be constrained to 2ºC - 3ºC above pre-industrial levels and RCP8.5 as a high warming scenario, with an average temperature increase of 3.7ºC (2.6 to 4.8) because it assumes emissions continue to rise throughout the 21st century.

Species occurrence data and the types of environments in which species prevail are important because SDMs are sensitive to sample size and biases in data distribution [1]. We tested the 19 bioclimatic variables for collinearity using Variance Inflation Factor (VIF), VIFcor functions, in R within the USDM package [51]. VIFcor measures the severity of multicollinearity in regression analysis and is a pairwise correlation that excludes the highly correlated variables stepwise. We applied the default threshold of 0.9, and variables above the threshold were excluded. Consequently, ten predictor variables were identified as suitable predictors for the *Erica* SDM **Table 1**.

Table 1. The identified ten suitable bioclimatic variables that were used to generate the *Erica* distribution models.

No	Environmental predictor variable	Code
1	Mean Diurnal Range (Mean of monthly (max temp - min temp))	Bio2
2	Mean Temperature of Wettest Quarter	Bio8
3	Mean Temperature of Driest Quarter	Bio9
4	Mean Temperature of Warmest Quarter	Bio10
5	Mean Temperature of Coldest Quarter	Bio11
6	Precipitation of Wettest Month	Bio13
7	Precipitation of Driest Month	Bio14
8	Precipitation Seasonality (Coefficient of Variation)	Bio15
9	Precipitation of Warmest Quarter	Bio18
10	Precipitation of Coldest Quarter	Bio19

3.3 Data Analysis

3.3.1 Model fitting, Prediction, and Evaluation

The modeling, including data preparation, cleaning, and calibration, was carried out following the SDMs r-script presented in [27]. The predictor variables were of the same spatial extent, resolution, origin, projection, and organized as raster ".tif" data. They were layer stacked (**Figure 4a**). The dependent (predicted values) and independent variables (bioclimatic predictors and *Erica* presence values) were identified, then the models were fitted. Cross-validation was carried out by creating a training and testing data set through random sampling and modeling with the data set of known occurrences (**Figure 4b**).

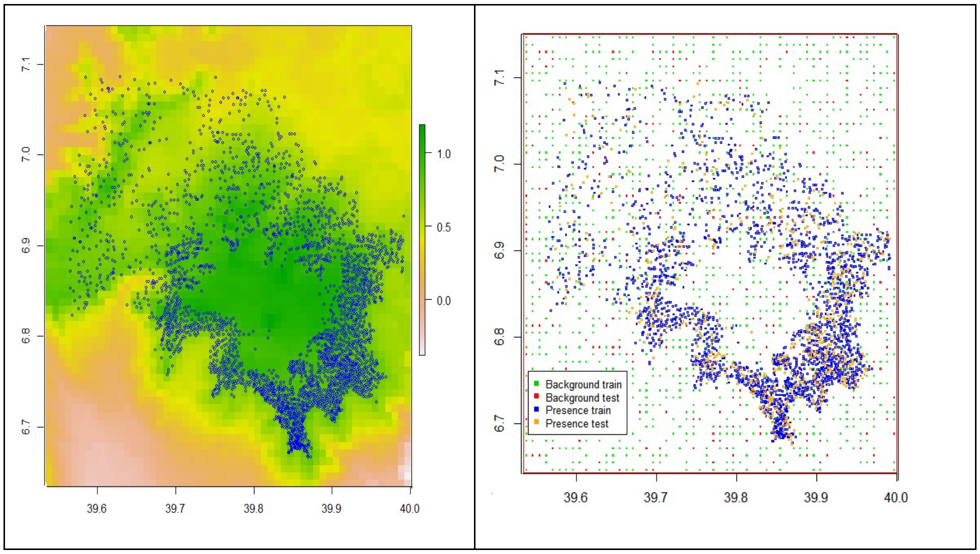


Figure 4: (a) Background: Layer stacked environmental predictors variables and sampled *Erica* (Blue circles) occurrence points, (b) Model fitting map with background train (green), background test (red), presence train (blue), and presence test (orange).

The *Erica* occurrence database, together with ten current and future bioclimatic predictors, were preprocessed with R version 3.6.0, using the packages "dismo" and "raster". The dismo package is used to predict the environmental similarity of any site to that of the locations of known occurrences of a species [15]. The "raster" package provides a spatial (geographic) data structure that divides a region into rectangles called "cells" or "pixels" that can store one or more values for each of these cells [29]. Subsampling within the range of our study area was run to reduce sampling bias and produce more balanced samples for model calibration. The modeling data sets were created through random sampling from a single data set. 1572 (75%) training and 487 (25%) test values were sampled for model evaluation.

Model performance was evaluated by calculating area Under the Curve (AUC). AUC is a measure of rank-correlation commonly used in SDM studies because it is insensitive to species prevalence and does not require a threshold value to convert probabilities to presence-absence [27]. A high AUC indicates sites with high predicted suitability (areas of known presence) in unbiased data, while AUC below the threshold indicates species absence. [14] in their model comparison, they found the best SDM models for each of their species distribution predictions had an AUC value of > 0.75; our models' AUC value was 0.79.

3.3.2 Modeling Methods

We selected four widely used correlative modeling methods Bioclim, Domain, Generalized Linear Methods (GLMs), and Support Vector Machines (SVMs), because of their wide use and good predictive performance. These algorithms have proven to perform well for species distribution modeling that uses species occurrence data and bioclimatic variables [14]. They all compute habitat similarity by comparing the values of bioclimatic variables to a percentile distribution of known species occurrence locations. The Bioclim algorithm has been one of the leading SDM packages for many years and remains widely used [6]. The most common climate data source for SDM studies, the WorldClim database, was created using climate interpolation methods developed applying BIOCLIM [6]. The Domain algorithm computes the Gower distance between environmental variables at any location and those at any known species occurrence locations [8]. The algorithm assigns to a place the distance to the closest known species occurrence. Generalized Linear Models (GLMs) are used extensively in species' distribution modeling because of their solid statistical foundation and ability to model ecological relationships realistically [2]. These models fit parametric terms, usually some combination of linear, quadratic, and/or cubic terms. GLMs are generalizations of ordinary least squares regression. Support Vector Machines (SVMs) [69] applies a simple linear method to the data but in a high-dimensional feature space that is non-linearly related to the input space.

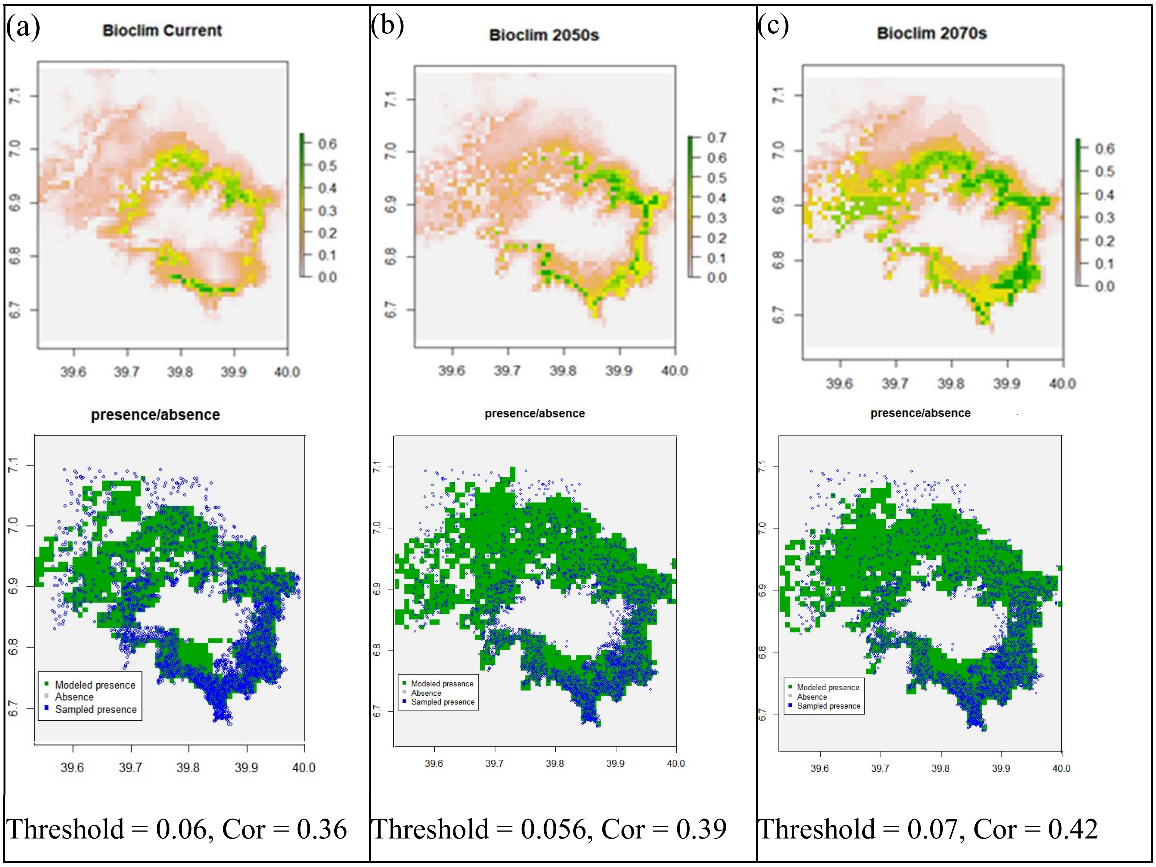
Finally, we applied model averaging to produce a more reliable model ensemble prediction. Model ensembles are fitted and evaluated to project potential species distributions in space and time [45, 50, 51]. The use of many models and applying model averaging to reduce reliance on a single model is suggested by many as a sound approach for better predictions [e.g., 27, 50, 63]. Hence, the four individual model predictions were ensembled based on their AUC values, and the mean predicted values were calculated. Furthermore, we calculated the difference between the averaged models of the different time steps, i.e., between current and the 2050s, and current and 2070s.

4. Results

The results of each modeling method are presented below. The probabilistic occurrence prediction maps obtained from the model runs, and corresponding presence/absence maps calculated based on each models threshold value are presented. These maps were built based on the most common threshold optimization method, the Cofusion matrix (max TPR (True Positive Rate) + TNR (True Negative Rate) (14, 27, 50). It is used to measure the performance of the classification model (50)(***see Supplementary material***). Each method has a different threshold depending on the model's algorism. The values above the threshold were marked as species presence, i.e., environmental conditions are optimal that allow Erica to satisfy its minimum requirements to flourish.

4.1 The Bioclim Predictions

The Bioclim model predicted *Erica's* current and future occurrence ranges with AUC values 0.82, 0.84, and 0.84 for current, the 2050s (RCP4.5), and the 2070s (RCP8.5), respectively (**Figure 5**). The probabilistic occurrence prediction maps *Erica's* presence with a threshold of 0.06, 0.056, and 0.07 for current (**Figure 5a)**, the 2050s (**Figure 5b),** and 2070s (**Figure 5c),** respectively. The future models predicted *Erica's* persistence within the current range while expanding towards western parts (the Web Valley and the area west of Lencha Ridge). This area is mainly covered with Afroalpine *Helichrysum* dwarf shrubs and herbaceous formations. Besides, the future models predicted *Erica's* consolidation within the current range, particularly on the eastern, norther and northeastern parts around Garba Gurecha, while shrinking from all lower altitudes of southwester and western parts.The Bioclim model predicted *Erica's* current distribution range well across the massif.

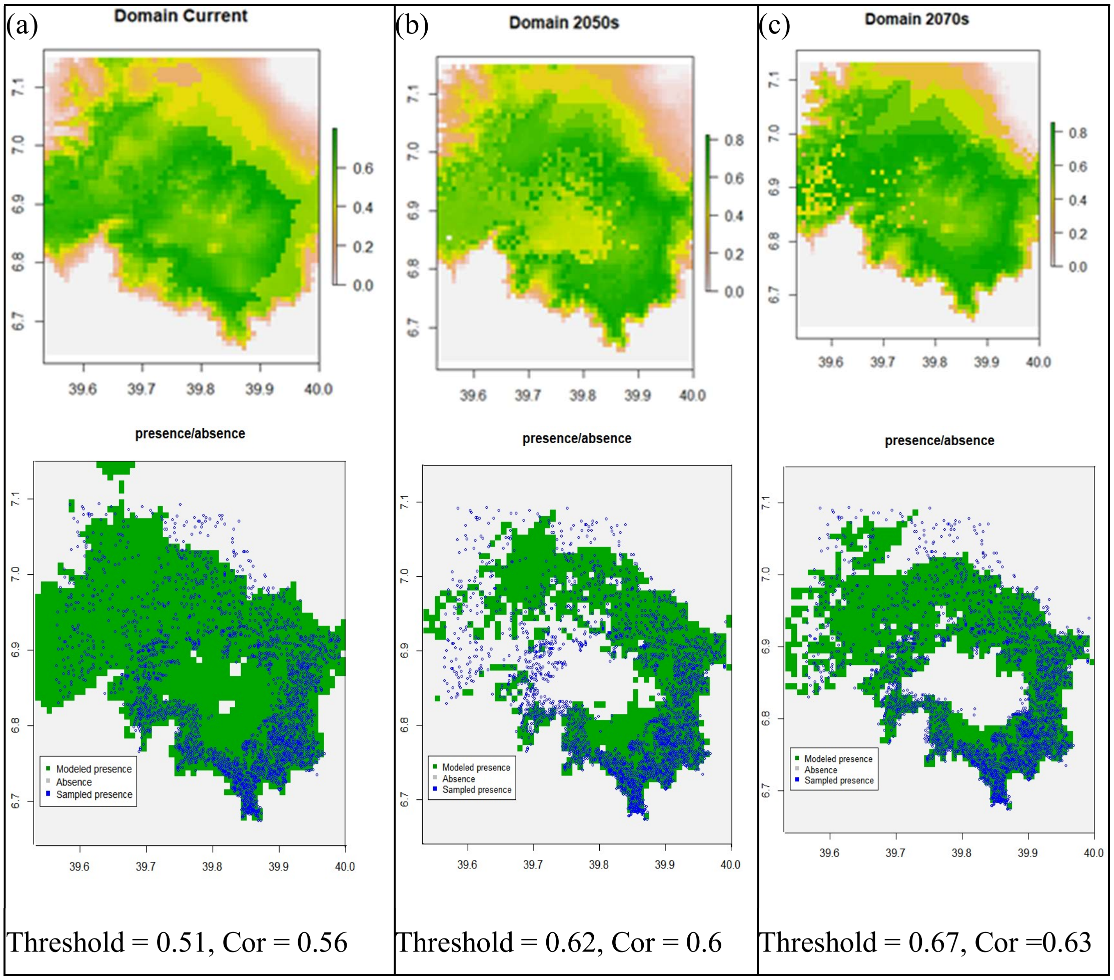


Threshold = 0.06, Cor = 0.36
Threshold = 0.056, Cor = 0.39
Threshold = 0.07, Cor = 0.42

Figure 5. Bioclim's prediction maps of probability of *Erica* occurrence for current, future 2050s and future 2070s, and their respective presence/absence maps compared with sampled presence sampling points. A gray area represents absolute absence (unsuitable habitat), green indicates modeled presence (suitable habitat), while blue circles represent sampled presence points.

4.2 The Domain Predictions

The Domain model predicted *Erica*'s current and future occurrence ranges with model AUC values 0.81, 0.83, and 0.83 for current, the 2050s (RCP4.5), and the 2070s (RCP8.5), respectively (**Figure 6**). The probabilistic occurrence prediction maps with optimization threshold 0.51, 0.62, and 0.67 for current (**Figure 6a)**, the 2050s (**Figure 6b)** and 2070s (**Figure 6c)** respectively. The Domain method, unlike the Bioclim, modeled the Afroalpine main habitat, the Sanetti Plateau, as a highly suitable *Erica* habitat, even area contemporarily no inhabited by *Erica*. The future models, however, predicted successive consolidation of *Erica* within the current southeatern eastern and northeaster parts, and retraction from the western and northern during the 2050s, and recolonization of the western and northern parts by 2070s. The future models does not show strong upwards expansion towards the top of the afraolpine plateau, the Sanetti Plateau. They futher indicated habitat simplification and retracting of *Erica* from all its lower ranges on the norther, western and southwestern parts.

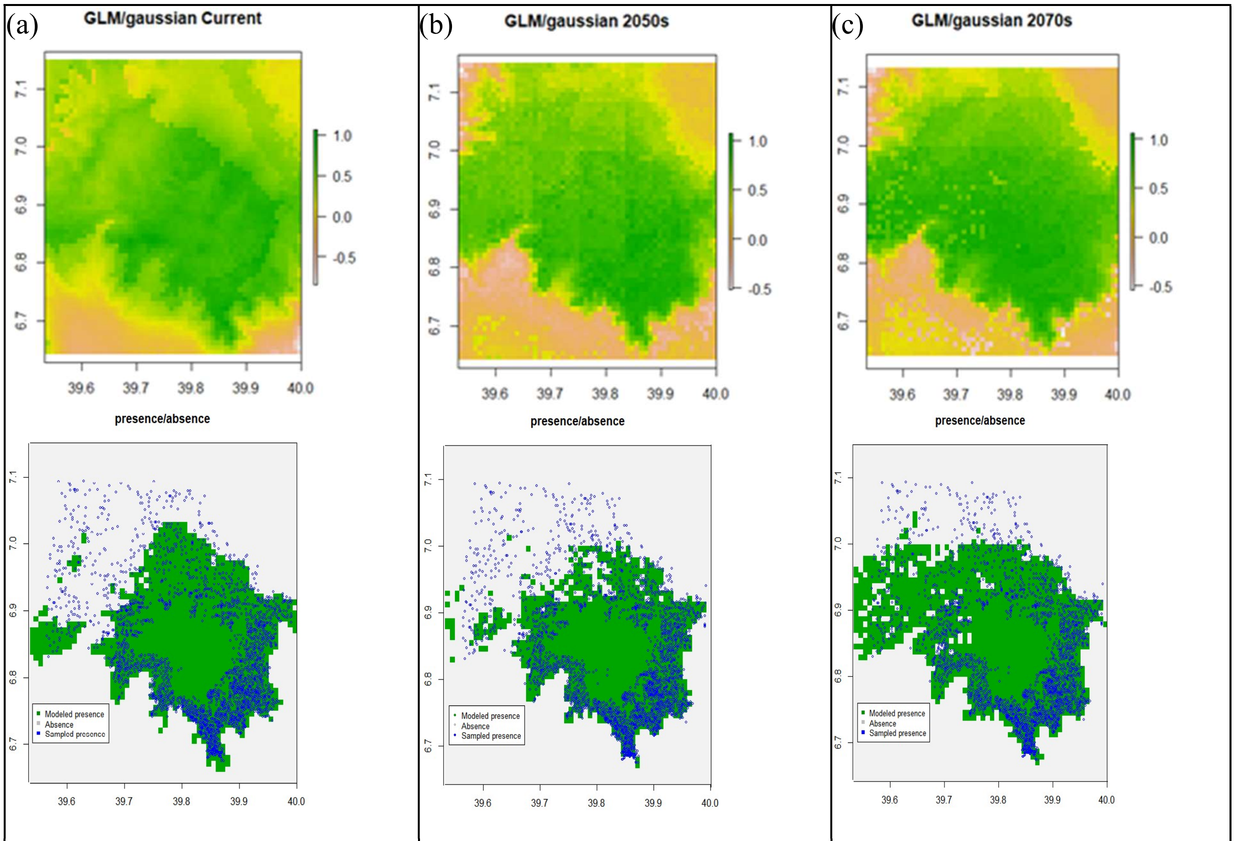


Threshold = 0.51, Cor = 0.56 Threshold = 0.62, Cor = 0.6 Threshold = 0.67, Cor =0.63

Figure 6. Domain's prediction maps of probability of *Erica* occurrence for current, future 2050s and future 2070s, and their respective presence/absence maps compared with sampled presence sampling points. A gray area represents absolute absence (unsuitable habitat), green indicates modeled presence (suitable habitat), while blue circles represent sampled presence points.

4.3 Generalized Linear Model (GLM)

The GLM model predicted *Erica*'s current and future occurrence ranges with model AUC values 0.83, 0.86, and 0.81 for current, the 2050s (RCP4.5), and the 2070s (RCP8.5), respectively (**Figure 7**). The probabilistic occurrence prediction maps with optimization threshold 0.62, 0.75, and 0.73 for current (**Figure 7a)**, the 2050s (**Figure 7b)** and 2070s (**Figure 7c)** respectively. The future prediction indicated *Erica's* substantial north and northwestern ward expansion with time while losing substantially in all the lower ranges. The GLM model similar to the Domain method modeled the Afroalpine main habitat, the Sanetti Plateau, as a highly suitable *Erica* habitat, even area contemporarily no inhabited by *Erica* for all time steps. The current model fail to model some parts of the current Erica habitats, such as the norther, western and southwestern parts of the massif (the Web Valley and the area west of Lencha Ridge). Both future projections indicate a solid midaltitude persistence of *Erica* within its current range, while retreating from all lower ranges of the southern and eastern parts of the massif.



Threshold = 0.62, Cor = 0.6

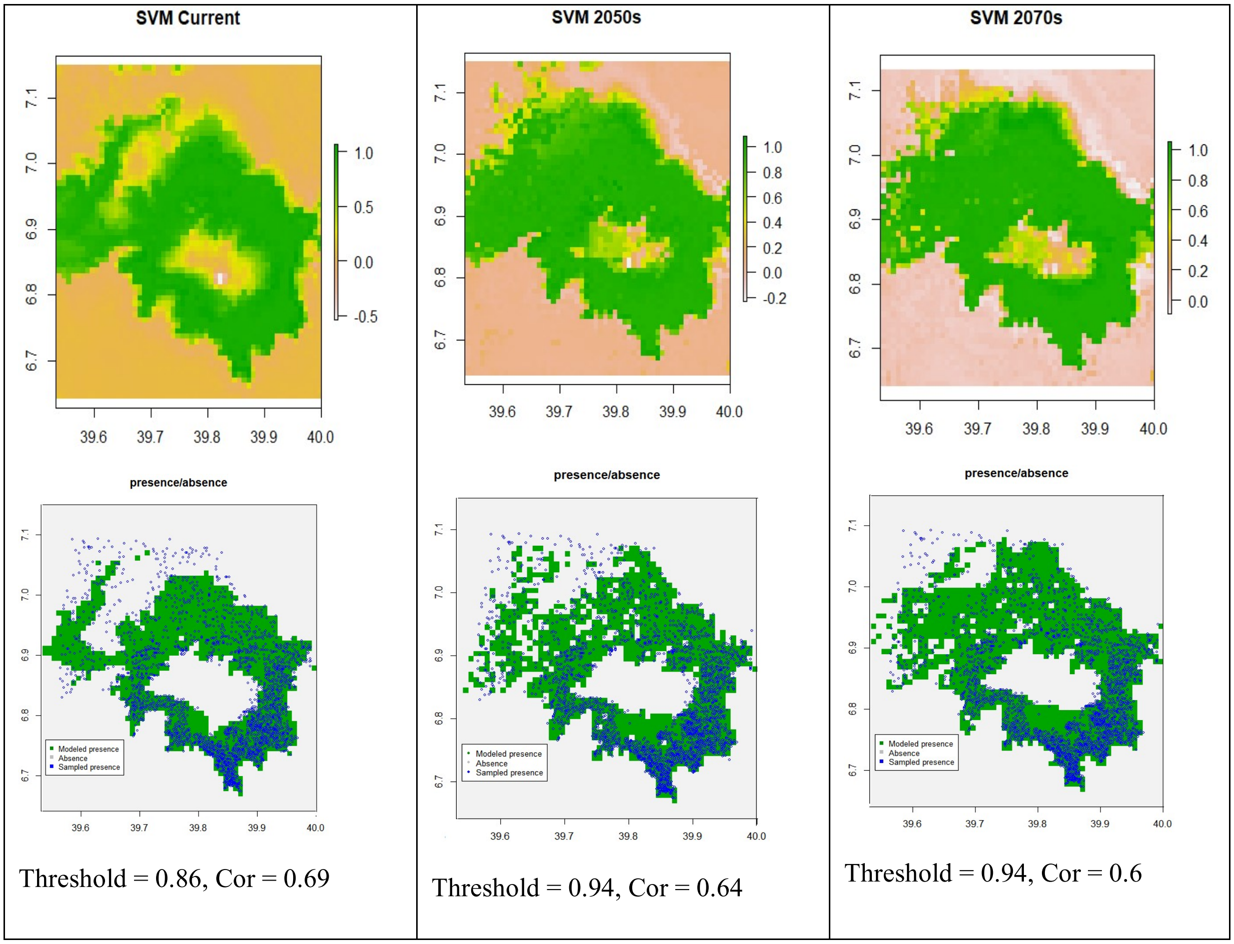
Threshold = 0.75, Cor = 0.62

Threshold = 0.73, Cor = 0.6

Figure 7. Generalized Linear Model's (GLM's) prediction maps of probability of *Erica* occurrence for current, future 2050s and future 2070s, and their respective presence/absence maps compared with sampled presence sampling points. A gray area represents absolute absence (unsuitable habitat), green indicates modeled presence (suitable habitat), while blue circles represent sampled presence points.

4.4 Support Vector Machine (SVM)

The SVM model predicted *Erica's* current and future occurrence ranges with model AUC values 0.86, 0.83, and 0.82 for current, the 2050s (RCP4.5), and the 2070s (RCP8.5), respectively (**Figure 8**). The probabilistic prediction maps obtained from the model runs and projections were split into binary presence-absence maps. The probabilistic occurrence prediction maps with optimization threshold 0.86, 0.94, and 0.94 for current (**Figure 8a**), the 2050s (**Figure 8b**) and 2070s (**Figure 8c**) respectively. The future predictions indicated a substantial consolidation of *Erica* within its current range with limited simplification on the western part, westward expansion into the current dispersed *Erica* habitat, slight expansion towards the Afroalpine range, and pronounced loss on all areas of the massifs lower ranges. Similar to the Bioclim model, SVM predicted *Erica's* current distribution range well across the massif, except for some the norther and northerwestern parts of the massive.



Threshold = 0.86, Cor = 0.69

Threshold = 0.94, Cor = 0.64

Threshold = 0.94, Cor = 0.6

Figure 8. Support Vector Machine's (SVM's) prediction maps of probability of *Erica* occurrence for current, future 2050s and future 2070s, and their respective presence/absence maps compared with sampled presence sampling points. A gray area represents absolute absence (unsuitable habitat), green indicates modeled presence (suitable habitat), while blue circles represent sampled presence points.

All four models predicted the loss of suitable habitat at lower ranges, especially at the southwester range, while the substantial gain on the mountain's western, northern, and eastern parts.

4.5 Ensemble Model Predictions

In order to optimize species distribution predictions and range shift under global change, rather than relying on a single "best" model, some authors [e.g., 27, 45, 50, 63] suggested using many models and applying model averaging. The results of our four individual model predictions were weighted by their AUC scores. To create the weights, [27] subtracted 0.5 (the random expectation) and squared the result to give additional weight to higher AUC values (**Figure 9: a-c**). The probabilistic occurrence prediction maps were split into binary presence-absence maps by averaging the optimization threshold of all four models. Hence, we used a threshold of 0.5.

The averaged model projected habitat loss on all the lower ranges of the current *Erica* distribution range in the future, substantial consolidation of *Erica* on most of its present habitats, significant expansion towards the western, northern, and eastern part of the massif, and the Afroalpine plateau, while retracting from the lower ranges of the eastern, southern and northeeatern parts of the plateau. Similar to the Bioclim and SVM modles the models ensseble produce occurrence prediction map that mirros the current range. The ensembled models built with model averaging are promising for modeling species distribution [27, 45, 50].

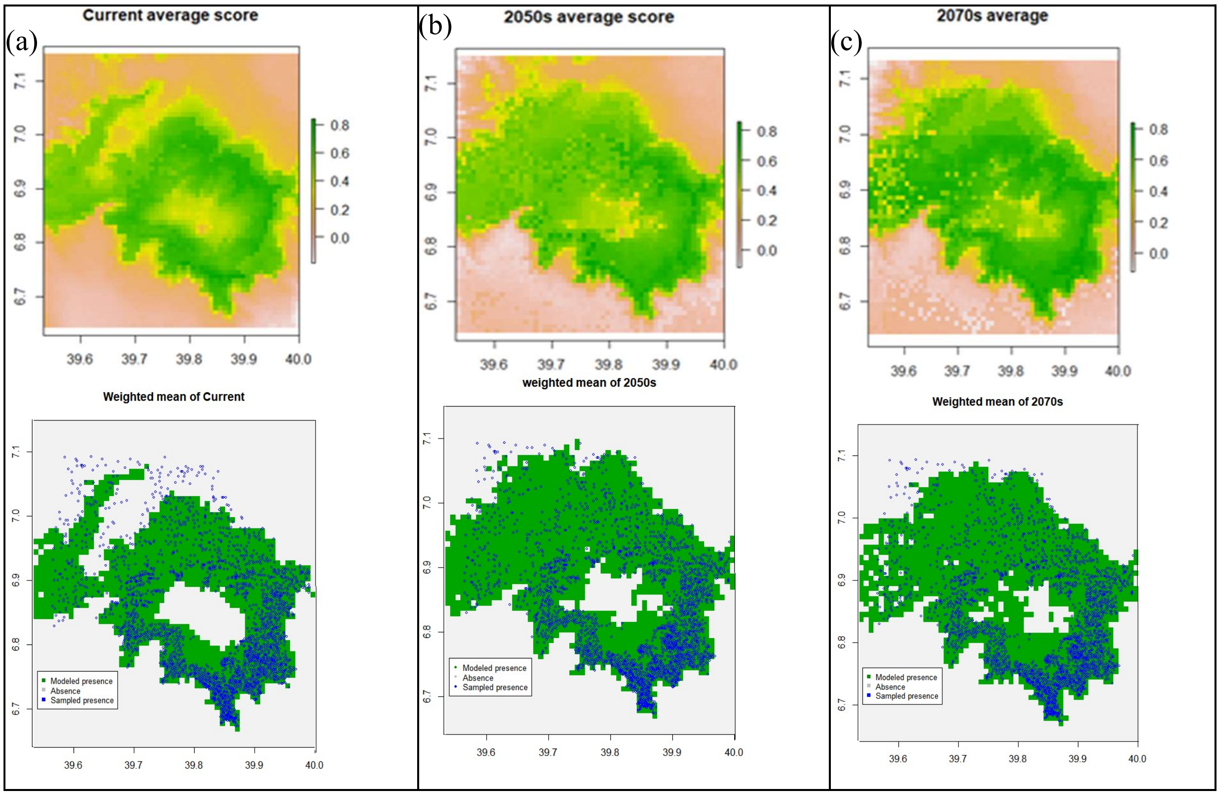


Figure 9. Ensemble four models' average of the three-time steps (Current, 2050s, and 2070s), and their respective presence/absence maps compared with sampled presence sampling points. A gray area represents absolute absence (unsuitable habitat), green indicates modeled presence (suitable habitat), while blue circles represent sampled presence points.

4.6 Change Calculation Between current and future predictions

Finally, we run a change detection matrix between the averaged models of the different time steps, i.e., between current and the 2050s (**Figure 10: 1a & 1b**) and current and 2070s (**Figure 10: 2a & 2b**). The difference between the current and 2050s shows *Erica* is projected to expand towards the western and northwestern parts of the mountains while maintaining its current range. The difference between the current and 2070s shows *Erica* is projected to continue expanding towards the western and northern parts of the mountains while maintaining a stronghold of its current range. However, *Erica* will retreat from all lower ranges and some parts of the current midaltitude distribution range towards the turn of the century.

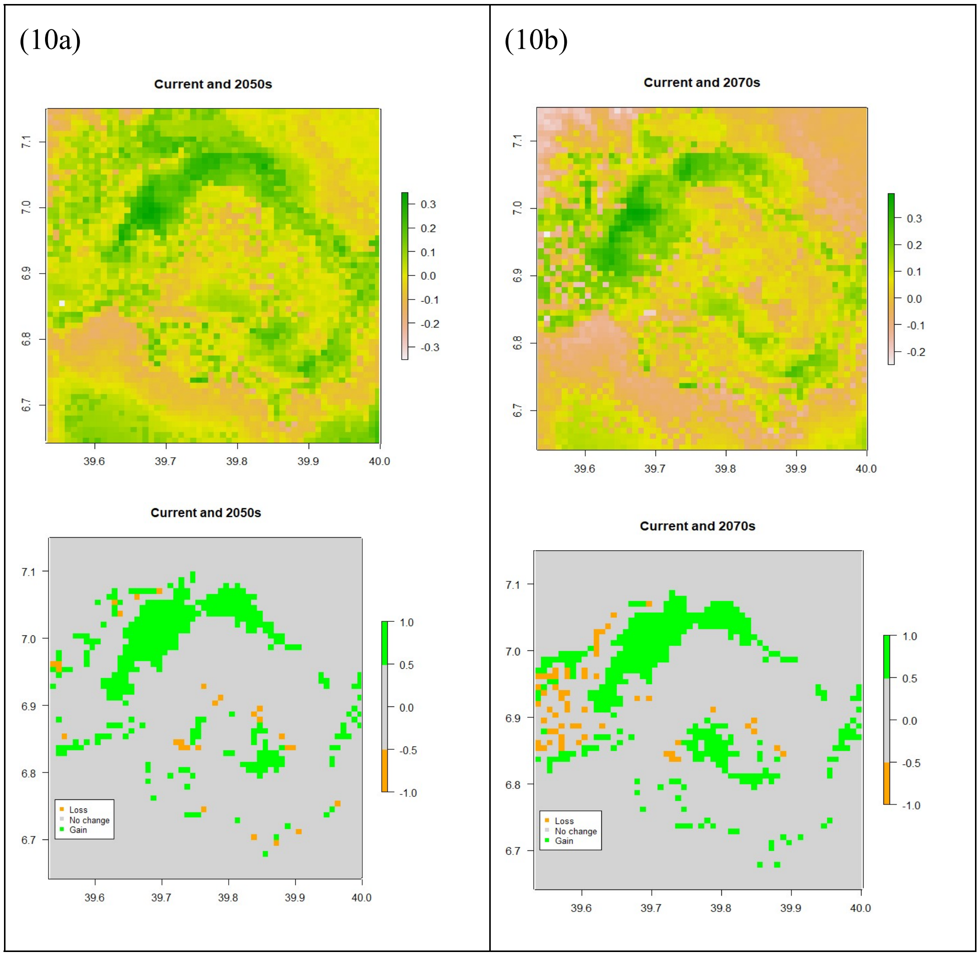


Figure 10. The difference between the averaged models' ensembles of the three time steps (current, 2050s, and 2070s). and their respective presence/absence maps. A gray area represents absolute absence (unsuitable habitat), green indicates modeled presence (suitable habitat), while orange area habitat lost during the span of the time step.

5. Discussion

The SDMs and the averaged ensemble models indicated that novel suitable habitats will be created due to climate change across the massive, which will likely be colonized by the ericaceous vegetation. *Erica* is expected to respond to the changes and prevail in the newly created suitable habitat. The different models projected its distribution and provided insight into *Erica's* future habitat such as the area of habitat gain (expansion) - western, northern, and eastern flanks of the massif and Afroalpine top; persistence and dominance - most of the midaltitude and its current range; and loss (reduction/ contraction) - most of the lower ranges of current distribution. It provided information about *Erica's* bioclimatic requirements and its current distribution range, including areas that are still remote and inaccessible areas that are free from human habitation.

Tropical alpine and montane ecosystems and the immense biodiversity they harbor are susceptible to climate change induced warming [7, 23, 32, 43]. It is likely that species with a more comprehensive thermal range, such as *Erica*, may track the novel niche and dominate the suitable habitat while receding from the unsuitable habitats. A 1.0ºC increase in mean annual temperature results in a range change of ~167 m in altitude but ~145 km^{-1} in latitude (based on a temperature lapse rate of -6.0ºC km^{-1} altitude and -6.9ºC 1000 km^{-1} latitude) [10, 37, 49]. The current temperature projections indicate that temperature regimes may shift upward between about 140 and 800 m across Afroalpine mountains [7].

Erica's response to climate change will not be different from what has been observed in other places. [10, 37, 43] projected an increase in temperature could induce a similar upward shift of altitudinal ecotone succession, leading to a loss of biodiversity at the ecosystem level. Furthermore, [54] and [19] indicated that mountain species would respond to climate change by migrating toward higher elevations and summits, in situ resilience of communities and species within microrefugia, adaptation, and evolution through genetic differentiation or extinction. [71], in their global analysis of the impacts of climatic change on the range of common species, indicated that on average 57 ± 7% of plants are likely to lose ≥ 50% of their current climatic range under RCP8.5.

Climate change is expected to play a significant role in shaping plant communities and displacing ecosystem boundaries along the Bale Mountains massif. As indicated by [61] in their global assessment, it may result in losses of natural habitats, leading to a rapid loss and extinction of species with their adaptations at lower elevations and mountain top. Furthermore, it may strongly reduce the Afroalpine habitat's total area, endangering the many Afroalpine habitat specialists and distinctively adapted endemics. The Bale Mountain Afroalpine plants may be disadvantaged and outcompeted by

Erica and similar species under climate change. *Erica* may take advantage and replace many Afroalpine endemics with restricted ranges due to its phenotypic plasticity, genetic adaptation to various habitats, high dispersal ability, and broader temperature tolerance. Besides, the movement towards a new climatic niche is a long evolutionary process for many Afroalpine specialists [3, 49, 57, 62]. In addition, the unique topography of the plateau does not allow an upward shift because of the smaller area of the few mountain summits. Therefore, the alpine plants are likely to face an ecological dead end [39].

The predicted *Erica* expansion towards the Afroalpine habitat in response to climatic change and the possible effect of these responses on the structure and function of Afroalpine ecosystems is essential. Under both future climate change scenarios (RCP4.5 and RCP8.5), many Afroalpine plants may decline and suffer local extinction. Overall, global extinction risks increase from 2.8% at present to 5.2% at the international policy target of a 2.0°C (RCP4.5) post-industrial rise, which is above the [33] target cumulative emissions of CO_2 and future non-CO_2 radiative forcing below or at max 1.5°C warming. If the Earth warms by 3.0°C, the extinction risk may rise to 8.5%. One of the current businesses as usual trajectory RCP 8.5 (up to ~ 4.3 °C rise), climate change threatens one in six species (16%) of global species [68]. However, in the Bale Mountains [39], estimated altitudinal range shifts following a temperature increase of 2.0 °C cause the potential local extinction of 8.7% of all endemic species, and 3.0 °C or 4.0 °C (under RCP8.5) about 36% (of 41 endemic species) local extinction. Plants threatened with extinction include *Sedum mooneyi* M.G. Gilbert, *Anthemis tigreensis* J. Gay ex A.Rich., *Helichrysum harennensis* Mesfin, *Lobelia rhynchopetalum* Hemsl., *Senecio schimperi* Sch.Bip. ex Hochst., *Geranium arabicum* Forssk. subspp. Arabicum, *Carex simensis* Hochst. ex A. Rich., *Helichrysum horridum* Sch. Bip, and *Senecio inornatus* DC. are some of the species that are endangered with extinction in the Bale Mountains.

Along Ethiopian mountains, the alpine and subalpine vegetation have been oscillating in response to the changing climate [5, 22, 20, 53] and has been shaped by the change in temperature-related bioclimatic variables. [22, 9, 53] indicated that the Afroalpine vegetation was expanded towards the lower altitudes during the glaciation periods. [46] suggested that the Ericaceous Belt existing today as refugia on high mountains in East Africa would have been more typical of tropical Africa than the present lowland vegetation when the European and African continents came into contact 17 Ma in the mid-Miocene, and the area suitable for exploitation by *Erica* species along the recently uplifted areas would have been more significant than it is today.

Erica expansion might lead to considerable species replacement, local extinction, and a significant decrease in species richness, especially those endemics across the massif. In many mountain ecosystems, the topography of the steeper slopes may cause small-scale climatic heterogeneity and range of adjacent thermal niches allowing the coexistence of species with differing environmental tolerances in smaller areas [19, 76, 41]. However, in the Bale Mountains, due to the plateau's relatively flat topography, the role of microrefugia might not be significant. *Erica's* adaptation to a warming climate and dominance across the landscape will further be aided by gene flow from populations in already warmer areas of the species range [e.g., 7].

The Paris agreement [67] aims to keep global warming below 2.0°C while pursuing efforts to limit it to 1.5°C. [33] discusses how the global economy and socio-technical and ecological systems can transition to 1.5°C consistent pathways and adapt to global warming of 1.5°C. The impacts of climate change are enormous if global warming exceeds 1.5°C if the peak temperature is high (e.g., about 2.0°C). Some impacts of climate change may be long-lasting and/or irreversible, such as the loss of Afroalpine ecosystems.

SDMs enable us to build a basic understanding of vascular plants' distribution and diversity patterns in the face of climate change [54, 50]. To date, various SDMs based on projection indicate climate impact is inevitable and real. Therefore, adaptation at all levels of human and natural systems is essential. Adaptation and mitigation strategies such as alternative energy sources (biofuels, renewable resources like solar panels, efficient cooking stoves), improving the traditional agricultural systems (extension services, access to credit, changing crop varieties, and adoption of soil and water conservation strategies), local livelihood diversification, good governance, and information on future climate changes are crucial [11, 12].

Besides climate change, species are likely to respond to multiple environmental factors as the environmental conditions change significantly with increasing altitude. Environmental change factors such as geographic barriers that limit dispersal, topography, microrefugia, aspect, and local relief can blur the bioclimatic factors. Therefore, species may not occupy all suitable sites in the future [e.g., 19, 76, 41]. Besides, the effects of orography related precipitation and resource diversity may influence species distribution patterns. Other environmental factors such as atmospheric pressure, CO_2 concentration, length of the vegetation period, nutrient availability, and soil quality decreased with altitude. The frequency of cold and frosty nights and solar radiation that increase with altitude might restrict *Erica's* expansion towards the Afroalpine plateau.

6. Conclusions

The Bale Mountains' ericaceous vegetation will persist as the massif's critical ecosystem even under changing climate. All the models and the ensembled model projected areas of potentially suitable habitats of *Erica* at 1 km resolution and provided *Erica's* possible future distribution range within the Bale massif. We believe our findings will contribute to the scientific basis and understanding of the potential impacts of climate change on the ericaceous vegetation and associate Afroalpine flora and other species with high phenotypic plasticity and environmental range. Furthermore, our research that incorporate information from satellite technology, plot data, open source software, and modeling approaches suggests how climate change impacts, and biodiversity conservation management concerns of such remote but highly significant ecosystems could be addressed to improve and support local conservation efforts, set management priorities, and adaptation and mitigation strategies.

Climate change is likely to disrupt and alter the current spatial arrangement, diversity, and distribution of many endemic and non-endemic species of the Afroalpine range. In the Bale Mountains, both the upper and lower margins of distributions of *Erica* are highly likely to be affected. Hence, our modeling provided insight into *Erica's* future habitat such as the area of habitat gain (expansion) - western, northern, and eastern flanks of the massif and Afroalpine top; persistence and dominance - most of the midaltitude and its current range; and loss (reduction/ contraction) - most of the lower ranges of current distribution. However, *Erica's* future expansion will lead to considerable species replacement, local extinction, and a significant decrease in the species richness of those endemics on the Afroalpine plateau. Hence, ecosystems of the Afroalpine plateaus and associated unique flora and fauna are highly threatened by climate change.

Climate change adaptation strategies that support the conservation management of the Bale Mountains massif are necessary. Besides, some conservation management and adaptation measures are recommended, such as expanding the park's territory, creating a buffer zone, and limiting human activities and access to the Afroalpine region. Overall, there is a need for strict implementation of the existing biodiversity management strategies such as research, monitoring, and periodic assessments of ecosystem status are important.

7. Biosketches

Yohannes O Kidane (YOK) is interested in characterizing and protecting biodiversity in tropical landscapes and mountain ecosystems, global change issues, and ecosystems' response to climate change.

Samuel Hoffmann (SH) is a postdoctoral researcher at the Biogeography Department, University of Bayreuth. His research covers biogeography and macroecology, with a special interest in species diversity, climate change, remote sensing, and protected areas.

Mirela Beloiu (MB) is fascinated by forest dynamics and spatial patterns of tree species in mountain areas. Hence, her research focuses on the response of tree species to climate warming and drought.

Anja Jaeschke (AJ) is a postdoctoral researcher at the University of Bayreuth within the Department of Biogeography. Her research focuses on the application and methodological advancement of species distribution models to assess climate change impacts related to nature conservation and vector-borne diseases.

Carl Beierkuhnlein (CB) focuses, among other topics, on the role of biodiversity for ecosystem functioning, on the explanation of spatial patterns of biodiversity, and biogeography in the face of global change.

Author contributions: YK and CB conceived the ideas; YK collected the data; YK led the writing and analyzed the data; SH, MB, and AJ participated in writing and evaluating the results.

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9. References

1. Araújo, M.B., and Guisan, A. (2006). Five (or so) challenges for species distribution modeling. *Journal of Biogeography*. 33(10), 1677-1688. doi.org/10.1111/j.1365-2699.2006.01584.x
2. Austin M.P. (2002). Spatial prediction of species distribution: an interface between ecological theory and statistical modelling. *Ecological Modelling.* 157: 101-18.
3. Beierkuhnlein, C. (2007). Biogeografie. Die räumliche Organisation des Lebens in einer sich verändernden Welt. Eugen Ulmer Verlag, Stuttgart. 400 pp.
4. Bonnefille, R., (1983). Evidence for a cooler and drier climate in the Ethiopian uplands towards 2.5 Myr ago. *Nature*. 303, 487 - 491. doi.org/10.1038/303487a0
5. Bonnefille, R., Roeland, J.C., Guiot, J. (1990). Temperature and rainfall estimate for the past 40,000 years in equatorial Africa. *Nature*. 346, 347–349.
6. Booth, T.H., Nix, H.A., Busby, J.R., and Hutchinson, M.F. (2014). BIOCLIM: the first species distribution modelling package, its early applications and relevance to most current MAXENT studies. *Diversity and Distributions.* 20, 1–9. https://doi.org/10.1111/ddi.12144

7. Buytaert, W., Cuesta-Camacho, F., and Tobon, C. (2011). Potential impacts of climate change on the environmental services of humid tropical alpine regions. *Global Ecology and Biogeography*. 20, 19-33. doi.org/10.1111/j.1466-8238.2010.00585.x

8. Carpenter G., A.N. Gillison and J. Winter, (1993). Domain: a flexible modelling procedure for mapping potential distributions of plants and animals. *Biodiversity Conservation* 2: 667-680

9. Chala, D., Niklaus, E., Zimmermann, E.Z., Brochmann, C., and Bakkestuen, V. (2017). Migration corridors for alpine plants among the "sky islands" of eastern Africa: do they, or did they exist? *Alpine Botany*. 127, 133–144. DOI 10.1007/s00035-017-0184-z

10. Colwell, R.K., Brehm, G., Cardelús, C.L., Gilman, A.C., and Longino, J.T. (2008). Global warming, elevational range shifts, and lowland biotic attrition in the wet tropics. *Science*, 322, 258–261.

11. Di Falco, S., Veronesi, M., and Yesuf, M. (2011a). Does adaptation to climate change provide food security? A micro-perspective from Ethiopia. *American Journal of Agricultural Economics*. 93(3), 829-846. http://doi.org/10.1093/ajae/aar006

12. Di Falco, S., Yesuf, M., Kohlin, G., and Ringler, C. (2011b). Estimating the Impact of Climate Change on Agriculture in Low-Income Countries: Household Level Evidence from the Nile Basin, Ethiopia. *Environ Resource Economics*. 52, 457–478. DOI 10.1007/s10640-011-9538-y

13. Duveiller, G., Defourny, P., Descle'e, B., and Mayaux, P. (2008). Deforestation in Central Africa: Estimates at regional, national, and landscape levels by advanced processing of systematically distributed Landsat extracts. *Remote Sensing of Environment*. 112 (5), 1969-1981. doi:10.1016/j.rse.2007.07.026.

14. Elith, J., Graham, C.H., Anderson, R.P., Dudı´k, M., Ferrier, S., Guisan, A., Hijmans, R.J., et al., (2006). Novel methods improve prediction of 'species' distributions from occurrence data. *Ecograph*y. 29, 129-151.

15. Elith, J., Leathwick, J.R., and Hastie, T. (2009). A working guide to boosted regression trees. *Journal of Animal Ecology*. 77, 802-81.

16. Flantua, S.G.A., Payne, D., Borregaard, M.K., Beierkuhnlein, C., Steinbauer, M.J., Dullinge, S., Ess, F., Irl, S.D.H., Kienle, D., Kreft, H., Lenzner, B., Norder, S.J., Rijsdijk, K.F., Rumpf, S.B., Weigelt, P., and Field, R. (2020). Snapshot isolation and isolation history challenge the analogy between mountains and islands used to understand endemism. *Global Ecology Biogeography*. 29, 1651-1673. DOI: 10.1111/geb.13155

17. Foody, G.M. (2002). Status of land cover classification accuracy assessment. *Remote Sensing of Environment*. 80 (1), 185-201. doi:10.1016/S0034-4257(01)00295-4.

18. Gehrke, B., and Linder, H.P. (2014). Species richness, endemism, and species composition in the tropical Afroalpine flora. *Alpine Botany*. 124, 165 - 177.

19. Gentili, R., Baroni, C., Caccianiga, M., Armiraglio, S., Ghiani, A., and Citterio, S. (2015). Review: Potential warm stage microrefugia for alpine plants: Feedback between geomorphological and biological processes. *Ecological Complexity*. 21, 87 - 99. DOI.org/10.1016/j.ecocom.2014.11.006.

20. Gil-Romera, G., Adolf, C., Benito, B.M., Bittner, L., Johansson, M.U., Grady, D.A., Lamb, H.F., Lemma, B., Fekadu, M., Glaser, B., Mekonnen, B., Callejo, M.S., Zech, M., Zech, W., and Miehe, G. (2019). Long-term fire resilience of the Ericaceous Belt, Bale Mountains, Ethiopia. *Biological Letters*. 15, 20190357. http://dx.doi.org/10.1098/rsbl.2019.0357

21. Gizaw, A., Kebede, M., Nemomissa, S., Ehrich, D., Bekele, B., et al. (2013). Phylogeography of the heathers Erica arborea and E. trimera in the afro-alpine 'sky islands' inferred from AFLPs and plastid DNA sequences. *Flora*. 208, 453-463.

22. Gottelli, D., Marino, J., Sillero-Zubiri, C., Funk, S.M. (2004). The effect of the last glacial age on speciation and population genetic structure of the endangered Ethiopian wolf (*Canis simensis*). *Molecular Ecology*. 13, 2275–2286.

23. Grabherr, G., Gottfried, M., Pauli, H. (2010). Climate change impacts in alpine environments. *Geography Compass* 4, 1133–1153.

24. Hedberg, O. (1951). Vegetation belts of the East African mountains. *Sven. Bot. Tidskr*. 45, 140 - 202.

25. Hedberg, O. (1964). Features of Afroalpine Plant Ecology. Acta Phytogeographica Suecica. 49, 1-144. Uppsala, Sweeden. 144 pp.

26. Hedberg, O. (1986). Origins of the Afroalpine Flora. In High Mountains Tropical Biogeography. Eds. Vuilleumier F and Monasterio M. Published by Oxford University Press and the American Museum of Natural History. Oxford University Press. New York. 649 pp.

27. Hijmans, R.J., and Elith, J. (2017). Species distribution modelling with R. https://cran.r-project.org/web/ packages/dismo/vignettes/sdm.pdf (accessed July 2018).

28. Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., and Jarvis, A. (2005). Very high-resolution interpolated climate surfaces for global land areas. *International Journal of Climatology*. 25, 1965-1978.

29. Hijmans, R.J., van Etten, J. (2011). Raster: Geographic Analysis and modelling with Raster Data. R package version 1.8-39, URL http://CRAN.R-project.org/package=raster (accessed July 2018).

30. Hillman, J.C. (1986). Conservation in Ethiopia's Bale Mountains. *Endangered Species.* 3: 1-4.

31. Hillman, J.C. (1988). The Bale Mountains National Park Area, Southeast Ethiopia and its Management. *Mountain Research and Development,* 8 (2/3), 253-258.

32. IPCC, (2014). In Pachauri, R.K., Meyer, L.A. (Eds.), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Core Writing Team. IPCC, Geneva, Switzerland. 151 pp.

33. IPCC, (2018). Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.

34. Johansson, M. (2013). Fire and grazing in subalpine heathlands and forests of Bale Mountains, Ethiopia. Umea, Sweden: Swedish University of Agricultural Sciences.

35. Johansson, M.U., and Granström, A. (2014). Fuel, fire, and cattle in African highlands: traditional management maintains a mosaic heathland landscape. *Journal of Applied Ecology*. 51, 1396-1405. DOI: 10.1111/1365-2664.12291

36. Johansson, M.U., Frisk, C.A., Nemomissa, S., and Hylander, K. (2018). Disturbance from traditional fire management in subalpine heathlands increases Afro-alpine plant resilience to climate change. *Global Change Biology*. 24 (7), 2952-2964. DOI: 10.1111/gcb.14121.

37. Jump, A.S., Matyas, C., and Penuelas, J. (2009). The altitude-for-latitude disparity in the range retractions of woody species. *Trends Ecology and Evolution*, 24(12), 694-701. doi.org/10.1016/j.tree.2009.06.007.

38. Kidane, Y.O., Stahlman, R., and Beierkuhnlein, C. (2012). Vegetation dynamics, and land use and land cover change in the Bale Mountains, Ethiopia. *Environmental Monitoring Assessment*. 184 (12), 7473 - 7489. doi.org/10.1007/s10661-011-2514-8.

39. Kidane, Y.O., Steinbauer, M.J., and Beierkuhnlein, C., (2019). Dead end for endemic plant species? A biodiversity hotspot under pressure. *Global Ecology and Conservation*. 19, 1-12. doi.org/10.1016/j.gecco. 2019.e00670

40. Körner, C. (2007). The use of 'altitude' for ecological research. *Trends in Ecology and Evolution*. 22 (11), 569-574. doi.org/10.1016/j.tree.2007.09.006.

41. Körner, C.; Hiltbrunner, E. (2021). Why Is the Alpine Flora Comparatively Robust against Climatic Warming? *Diversity*. 13, 383. https://doi.org/10.3390/ d13080383

42. Kreyling, J., Wana, D., Beierkuhnlein, C., (2010). Climate warming and tropical plant species – consequence of the potential upslope shift of isotherms in southern Ethiopia. *Diversity and Distribution*. 16, 593-605. doi.org/10.1111/j.1472-4642.2010.00675.x.

43. Malcolm, J.R., Liu, C., Neilson, R.O., Hansen, A., and Hannah, L. (2006). Global warming and extinctions of endemic species from biodiversity hotspots. Conservation Biol. 20 (2), 538-548. https://doi.org/10.1111/j.1523-1739.2006.00364.x

44. Malhi, Y., and Wright, J. (2004). Spatial patterns and recent trends in the climate of tropical rainforest regions. Trans. R. Soc. Lond. B. 359, 311-329. doi: 10.1098/rstb.2003.1433 Phil.

45. Mateo, R.G., Felicı´simo, A.´M., Pottier, J., Guisan, A., and Mun˜oz, J. (2012.) Do Stacked Species Distribution Models Reflect Altitudinal Diversity Patterns? PloS ONE. 7(3): e32586. doi:10.1371/journal.pone.0032586

46. McGuire, A.F., Kathleen, A., Kron, K.A. (2005). Phylogenetic Relationships of European and African Ericas, *International Journal of Plant Sciences*. 162 (2): 311-318. https://doi.org/10.1086/427478

47. Messerli, B., and Ives, J.D. (1997). Mountains of the world: a global priority. edited by B. Messerli and J.D. Ives. Parthenon Pub. Group, New York. 495p.

48. Miehe, S., and Miehe, G. (1994). Ericaceous forests and heathlands in the Bale Mountains of South Ethiopia. Ecology and man's impact. Stiftung Walderhaltung in Africa, Hamburg.

49. Nagy, L., and Grabherr, G. (2009). The Biology of Alpine Habitats. Oxford University Press, Oxford.

50. Naimi, B., and Araújo, M.B. (2016). SDM: a reproducible and extensible R platform for species distribution modeling. Ecography. 39, 368–375. DOI: 10.1111/ecog.01881.

51. Naimi, B., Hamm, N.A.S., Groen, T.A., Skidmore, A.K., and Toxopeus, A.G. (2014). Where is positional uncertainty a problem for species distribution modeling? Ecography. 37 (2), 191-203.

52. Nsengiyumva, P. (2019). African Mountains in a Changing Climate: Trends, Impacts, and Adaptation Solutions. Mountain Research and Development 39(2), 1-8. https://doi.org/10.1659/MRD-JOURNAL-D-19-00062.1.

53. Ossendorf, G., Groos, A.R., Bromm, T., Tekelemariam, M.G., Glaser, B., Lesur, J., Schmidt, J., Akçar, N., Bekele, T., Beldados, A., Demissew, S., Kahsay, T.H., Nash, B.P., Nauss, T., Negash, A., Nemomissa, S., Veit, H., Vogelsang, R., Woldu, Z., Zech, W., Opgenoorth, L., and Miehe, G. (2019). Middle Stone Age foragers resided in high elevations of the glaciated Bale Mountains, Ethiopia. Science. 365 (6453), 583–587. DOI: 10.1126/science.aaw8942.

54. Peterson, A.T., Soberón, J., Pearson, R.G., Anderson, R.P., Martinez-Meyer, E., Nakamura, M., and Araújo, M.B. (2011). Ecological Niches and Geographic Distributions. Monographs in Population Biology -49. Princeton University Press, Princeton, and Oxford. 314 pp.

55. QGIS Development Team, (2018). QGIS Geographic Information System. Open-Source Geospatial Foundation Project. http://qgis.osgeo.org.

56. R Core Team, 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing [Internet]. http://www.R-project.org/.

57. Razgour, O., Kasso, M., Santos, H., and Juste, J., 2020. Up in the air: Threats to Afromontane biodiversity from climate change and habitat loss revealed by genetic monitoring of the Ethiopian Highlands bat. Evol Appl. 00,1–13. https://doi.org/10.1111/eva.13161.

58. Smeeton, N. C. (1985). Early History of the Kappa Statistic. *Biometrics*, 41(3), 795–795. http://www.jstor.org/ stable/2531300

59. Smith, A.P., and Young, T.P. (1987). Tropical alpine plant ecology. Annual Review of Ecology and Systematics. 18, 137- 158.

60. Steinbauer, M., Field, R., Grytnes, J.A., Trigas, P., Ah-Peng, C., Attorre, F., Birks, H.J.B., Borges, P.A.V., et al., (2016). Topography-driven isolation, speciation and a global increase of endemism with elevation, Global Ecology and Biogeography. 25(9), 1097–1107. doi: 10.1111/geb.12469.

61. Steinbauer, M.J., Grytnes, J.A., Jurasinski, J., Kulonen, A., et al., (2018). Accelerated increase in plant species richness on mountain summits is linked to warming. Nature. https://doi.org/10.1038/ s41586-018-0005-6.

62. Testolin, R., Attorre, F., Borchardt, P., Brand, R.F., Bruelheide, H., Chytrý, M., De Sanctis, M., Dolezal, J., Finckh, M., et al., (2021). Global patterns and drivers of alpine plant species richness. Global Ecol Biogeogr. 00, 1–14. DOI: 10.1111/geb.13297.

63. Thuiller, W. (2003). BIOMOD - optimizing predictions of species distributions and projecting potential future shifts under global change. *Global Change Biology*. 9: 1353-1362.

64. Uhlig, S., and Uhlig, K. (1991). Mountain Chronicles. Studies on the Altitudinal Zonation of Forests and Alpine Plants in the Central Bale Mountains, Ethiopia. Mountain Research and Development. 11, 153-256.

65. Umer, M., Lamb, H.F., Bonnefille, R., Lezine, A.M., Tiercelin, J.J., Gibert, E., Cazet, J.P., Watrin, J. (2007). Late Pleistocene Holocene vegetation history of the Bale Mountains, Ethiopia. Quatern Sci Rev .26, 2229–2246.

66. United Nations Framework Convention on Climate Change (UNFCCC), (2015). The Paris Agreement. https://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english_.pdf. Accessed November 19, 2021.

67. United States Geological Survey (USGS), (2018). Landsat Archive. Landsat standard data products. http://landsat. usgs.gov. Accessed July 17, 2018.

68. Urban, M.C. (2015). Accelerating extinction risk from climate change. *Science.* 348, 571–573. DOI: 10.1126/science. aaa4984

69. Vapnik, V. (1998). Statistical Learning Theory. Wiley, New York.

70. Vuilleumier, F., and Monasterio, M., 1986. Introduction: High tropical Mountain Biota of the World. In Vuilleumier, F., and Monasterio, M. (Eds) High Mountains Tropical Biogeography. Oxford University Press. New York.

71. Warren, R., VanDerWal, J., Price, J., Welbergen, J.A., Atkinson, I., Ramirez-Villegas, J., Osborn, T.J., Jarvis, A., Shoo, L.P., Williams, S.E., and Lowe, J. (2013). Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. *Nature Climate Change*. 3, 678-682. DOI: 10.1038/NCLIMATE1887

72. Wegmann, M., Leutner, B., and Dech, S. (2016). Remote Sensing and GIS for Ecologists: Using Open Software. Exeter: Pelagic Publishing, UK. 333 pp.

73. Wesche, K. (2003). The importance of occasional droughts for Afroalpine landscape ecology. Journal of Tropical Ecology. 19, 197-208. doi.org/10.1017/S0266467403003225

74. Wesche, K., Cierjacks, A., Assefa, Y., Wagner, S., Fetene, M., and Hensen, I. (2008). Recruitment of trees at tropical alpine treelines: Erica in Africa versus Polylepis in South America. *Plant Ecology and Diversity*. 1, 35–46. doi.org/10.1080/17550870802262166.

75. Wesche, K., Miehe, G., and Kaeppeli, M. (2000). The significance of fire for Afroalpine ericaceous vegetation. *Mountain Research and Development*. 20, 340-347. DOI:10.1659/0276-4741(2000)020[0340:TSOFFA]2.0. CO;2

76. Winkler, M., Lamprecht, A., Steinbauer, K., Hülber, K., Theurillat, J.P., et al. (2016). The rich sides of mountain summit a pan-European view on aspect preferences of alpine plants. Journal of Biogeography. 43 (11), 2261-2273. doi.org/10.1111/jbi.12835.

77. World Climate Research Program (WCRP), (2021). Coupled Model Intercomparison Project 5 (CMIP5). https://esgf-node.llnl.gov/projects/cmip5

Chapter 3

Dead end for endemic plant species? A biodiversity hotspot under pressure

Yohannes O Kidane[1,*], Manuel Jonas Steinbauer[2], and Carl Beierkuhnlein[1,3,4]

[1]Department of Biogeography, Bayreuth, University of Bayreuth, Germany
[2] GeoZentrum Nordbayern, Department of Geography and Geosciences, Friedrich-Alexander University of Erlangen-Nürnberg (FAU), Loewenichstr. 28, 91054, Erlangen, Germany
[3] Bayreuth Center of Ecology and Environmental Research (BayCEER), Bayreuth, Germany
[4] Geographical Institute Bayreuth (GIB), Bayreuth, German
* **Corresponding author:** Yohannes O Kidane

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Abstract

Tropical high mountains are hosting important hotspots of biodiversity in small, primarily remote areas. Recently, these precious ecosystems are under threat from land use change and climate change coupled with other local drivers of biodiversity loss. Along the East African Afroalpine ecosystems, the area above the treeline has experienced long-term spatial isolation and extreme climatic conditions (climatic factors such as low mean temperature, diurnal freeze-thaw cycles, and other energy-related factors) which lead to the formation of "Sky Island" like ecosystems that are rich in endemics and unique. The Bale Mountains of Ethiopia are home to the largest tropical alpine plateau in Africa. However, there are no spacious high summits that provide space for an upward shift of species. Here, we studied plant species diversity and distribution patterns and tested potential future impacts of climate change-induced warming on those patterns. This study is based on distribution data acquired from nested circular plots along an elevational gradient ranging from 2000m asl to the highest elevation (4385m asl). Hump-shaped species richness patterns on both aspects, i.e. the dry north-eastern and the wet monsoon exposed south-western escarpment. In addition, the proportion of endemic species increases monotonically towards the summit on all slopes. Based on our data and literature, we project future climate impact for three regional warming scenarios (+ 2°C, + 3°C and + 4°C). We quantify the future range of 448 plant species based on their current occurrence records and applying a lapse rate of 0.6°C per 100m of elevation. We find that future climate change would significantly alter species distribution patterns with pronounced impact on the unique ecosystems and endemic species restricted to the Afroalpine plateau. Very likely this will be leading to the extinction of many endemic species.

Keywords: Elevational gradients; Tropical mountains; Sky Islands; Range shifts; Endemic species; Endemism; Extinction

1. Introduction

Ethiopia is characterized by the largest montane areas in tropical and subtropical Africa, which are at the center of East Africa's hotspot of diversity (Mutke et al. 2001). Especially, the Afroalpine ecosystems on isolated mountains (the Ethiopian "sky islands") harbor a large number of unique endemic species (Hillman 1988; Friis et al. 2005). The significance and influence of these mountains, in terms of biodiversity conservation and other ecosystem services, exceed their spatial limits reaching further beyond the surrounding lowlands. Owing to their agricultural productivity, favorable climate, safety, and rich natural resources, Ethiopia's mountains are centers of ancient human residence, sources of livelihood, and socioeconomic activities. Altitudinal gradients of plant diversity are conspicuous along these mountains.

Systematic approaches to defining and understanding Plants' diversity and distribution patterns across spaces and time have been a central concern of biogeographers. The altitudinal patterns of diversity and the underlying causes are poorly understood (Sanchez-Gonzalez & Lopez-Mata 2005). Especially with climate change understanding these patterns and analyzing their underlying mechanisms is crucial (Jentsch & Beierkuhnlein 2003). Generally, species richness tends to decrease with altitude (Bruun et al. 2006). Nevertheless, several studies have also documented a nonmonotonic pattern of species richness (Grytnes 2003; Bhattarai & Vetaas 2003). The most commonly observed pattern of diversity is a midaltitude bulge (Rahbek 2005; Steinbauer et al. 2018).

Climate change induced warming is expected to impact plant diversity and distribution at all levels starting from single species to biomes (Parmesan 2006). Increase in temperature will result in habitat quality deterioration and instability which could lead to the loss of species, alteration of species diversity, abundance, and distribution (Enquist 2002; Davis et al. 2005; Malcolm et al. 2006; Lovejoy 2008; Jump 2009; Kreyling et al. 2010; Steinbauer et al. 2018). It will also result in alterations in population dynamics of native species that may enhance climate mediated biological invasion, alter community interactions and structure, and ecosystems functions (Walther et al. 2002). Small shifts in the thermal isotherm along altitudinal gradients may allow species to adapt and remain within their tolerance limits or may be compensated by adaptation, and/or compel them to move to novel environmental conditions. However, considerable warming is likely to result in altitudinal range shifts via dispersal or migration and local loss of populations which means extinction in the case of spatially restricted endemic species (Enquist 2002; Davis et al. 2005; Malcolm et al. 2006; Steinbauer et al. 2018).

Africa's tropical alpine ecosystems are experiencing the direct and indirect impacts of climate change, human population growth and socio-economic development (Buytaert et al. 2011; Jacob et al. 2014). Climate change represents perhaps one of the most pervasive and serious of the various threats to biodiversity (Malcolm et al 2006; Jump et al 2009). More specifically, for East African mountains, climate change is expected to result in altitudinal range shift and range contraction (Kreyling et al. 2010).

The Bale Mountains of south-central Ethiopia form the largest continuous area above 3000m in Africa, supporting the most extensive area of Afroalpine and subalpine ericaceous vegetation on the continent (Miehe and Miehe, 1994). The contiguous mountain massifs were one of the most extensively glaciated mountains during the Pleistocene, which shaped their recent geomorphology (Bonnefille 1983; Osmaston et al. 2005). Consequently, only three small peaks (Tullu Dimtu 4385m asl, Batu 4307m asl, and Konteh 4132m asl.) of total area 99.1km^2 reach elevations beyond 4100m asl, while the largest part of the plateau is characterized by homogenous topography. The area of the plateau which extends between 3100 - 4385m asl is 2020km^2. Nevertheless, the area above the treeline at approximately 3800m asl is very spacious and extents up to 480.5km^2 forming the largest area of afro-alpine ecosystems.

The Bale Mountains are hosting a high priority conservation area of global significance. They represent one of the 34 biodiversity hotspots and are listed by UNESCO as tentative world heritage site and biosphere reserve (Mittermeier et al. 2004). Further, they are within the range of Endemic Bird Areas analysis of BirdLife International (Stattersfield et al. 1998). Nevertheless, given their significance, they have received little international attention.

Along the Bale Mountains, from the tropical rainforest to the treeless Afroalpine meadows, an ordered sequence of vegetation zones stretches along the altitudinal gradients. Like many other tropical mountains in Africa and Asia (Parmesan 2006), no study has so far systematically analysed these altitudinal biotic patterns along the Bale Mountains. In addition, to their significance in providing more information to evaluate impact of future climate changes, such elevation gradients on isolated mountains also pose unique opportunities to study the effect of ecological and evolutionary processes (Steinbauer et al. 2016a, 2016b). The Island-like nature of these ecosystems permits study of how isolation and habitat area affect community structure and dynamics (Itescu 2018). Moreover, major advances in the understanding of patterns in species composition and diversity are acquired from such gradient analysis (Schweiger et al. 2016).

There are few ecological studies that focus on the biogeography of the area, studies that explore vascular species richness, especially endemic species richness along altitudinal gradient and climate change impacts on future species distributions do not exist. Such studies are important, because (1) the Afroalpine plateau is significantly and uniquely representative. The Sanetti plateau on the Bale mountains is one of the largest continuous Afroalpine habitats. The total area of Africa's tropical Afroalpine ecosystems is less than 5,000 km^2 (Körner et al. 2017, Gehrke and Linder 2014), of which as much as 27% is in the Bale mountains (1354 km^2, area above 3400m a.s.l., own calculations); and (2) unique diversity is under immediate threat from coupled impact of local intensification of human activities and climate change.

Therefore, our study will: (1) analyse plant species-diversity-richness and endemic-diversity-richness relationships along elevation gradient of the Bale Mountains aiming at a better understanding of spatial patterns in diversity within the hotspot area; and (2) demonstrate direct consequences of warming induced thermal isotherm shift for the diversity, abundance and distribution of species. Our findings may contribute (1) to frame conservation management strategies for biodiversity in the face of climate change and increasing human activities; and (2) to add a voice to the calls for bringing international attention in recognizing the Afroalpine habitat as a globally significant biodiversity hot spot.

2. Material and methods

2.1 Study area

The Bale Mountains are located 400 km south of Addis Ababa among those Ethiopian high mountain chains located on the South-eastern flanks of Great East African Rift Valley (Figure 1). The Bale Mountains National Park (hence forth BMNP) covering above 2200km^2 of afromontane and Afroalpine habitats is located within the mountains. These mountains are one of the last remaining pristine Afroalpine biodiversity hotspots in the tropics and one of the last remaining habitats for most Bale Endemic plants. Generally, Africa's Afroalpine ecosystems exclusively occur along the Great Rift Valley as small and isolated patches (Buytaert et al. 2011).

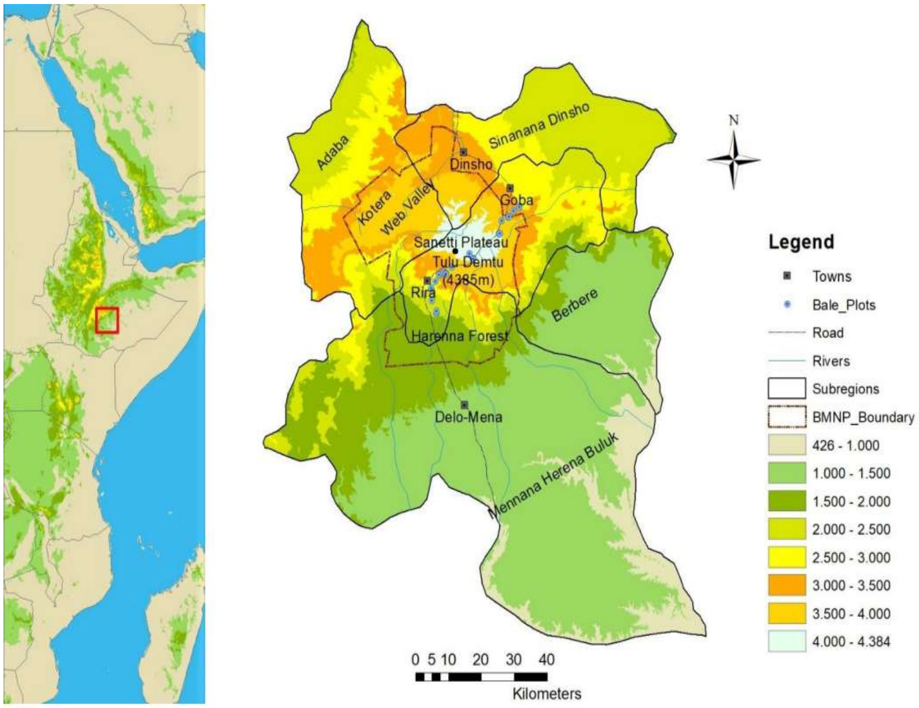

Figure 1: The study area and the surrounding administrative sub-zones. The Ethiopian Bale mountains are located southeast of the Great East African Rift Valley. Sample plots follow southwestern and north-eastern elevational gradients (light blue circles, total number of plots = 31).

The Bale Mountains are located at the convergence of the wet East African and dry northeast African mountains of southeast Ethiopia. They are important water sources for the dry lowlands feeding many perennial mountain springs and more than 40 small rivers discharging into the five major rivers Web, Wabe Shebele, Welmel, Dumal and Genale (Hillman 1986; Dullo et al. 2015). Historically, the Mountains have experienced a high degree of climate variability and change (Peyron et al. 2000; Umer et al. 2007; Kuzmicheva et al. 2013; Kuzmicheva et al. 2014). Contemporary climate within the area varies from northeast to southwest mainly due Orographic effects (Uhlig 1990; Miehe and Miehe 1994). The south and southwest facing slope is more humid with subtropical climate, high annual rainfall (up to 1500mm/year), and with the dry season lasting only about two months. While the north and northeaster parts receive from 800 to 1100mm/year of annual rainfall and a wet season from June to September. Along altitude, precipitation increases up to an elevation of 3,850m asl, but then decreases towards the summits (Hillman 1986). In the region the rainfall pattern is slightly bimodal, with a peak from April to May followed by a second peak from August to October.

The Afroalpine habitats are characterized by strong seasonal and diurnal temperature fluctuations and night frost. On the Plateau, an extreme diurnal temperature range of about 40°C (-15°C to + 26°C) has been recorded during the dry season (Hillmann 1986). Night frost is common year-round above 4000m asl.

Consequently, the biota experience extreme diurnal temperature fluctuation, labelled as "summer every day and winter every night" (Hedberg 1964). The unique climatic conditions supported the evolution of highly adapted plant species like the iconic specialized alpine giant rosette plants *Lobelia rhynchopetalum* and other Bale endemic plants such as *Alchemilla haumanii, Anthemis tigreensis, Agrostis gracilifolia subsp. Parviflora, Droguetia iners subsp. Pedunculate, Helichrysum gofense, Sedum baleensis, Sedum mooney, Senecio unionis* and *Geranium arabicum.*

The Bale Mountains are fragmented by numerous volcanic plugs, peaks, alpine lakes, and rushing mountain streams that descend into deep rocky gorges on their way to the lowlands. The mountains geology is characterized by a vast high elevation volcanic plateau over much older volcanic material formed during the spreading of the Great East African Rift Valley system (Friis et al. 2005). The petrography is dominated by alkali basalt and tuffs, with occasional rhyolites (Uhlig and Uhlig 1991). They have old geological formations, older than that of the Rift Valley (Mohr 1971).

The uppermost part the Sanetti plateau is bordered by abrupt escarpments to the south, which fall from above 4000m asl to below 2000m asl within a short aerial distance. The north and northeast are deeply dissected valleys descending to the northern slope, while to the west marks of ancient lava flows form spectacular bluffs (Osmaston et al. 2005). Soils in the area tend to be shallow, gravelly, and recently derived from stratigraphically youngest units derived mainly from the Miocene basalt and trachyte lavas that lay over Mesozoic sediments (Umer et al. 2007). They consist of a relatively silty loam, clay, sandy loam and silty loam of reddish brown to black colour.

2.2 Vegetation

Vegetation zonation of the Bale Mountains resembles that of other East African Mountains (Hedberg 1951, Uhlig and Uhlig 1991; Friis 1992; Miehe and Miehe 1994), and it lies within the Somali–Masai regional centre of endemism (White 1983). The Mountains massif exhibits a steep gradient of ecological zones (Table 1) ranging from tropical rainforests to Afroalpine vegetation (Kidane et al. 2012). The historical climate dynamics, topography driven micro climate and the resulting habitat and resource diversity played a crucial role in shaping the contemporary vegetation. This habitat variation combined with the unique climate, large extent and the isolation of the Bale Mountains from other Ethiopian highlands, west of the Great Rift Valley, have resulted in high endemism (Friis et al. 2005). This plant biodiversity hot spot provides habitat for one of the largest concentrations of endemic plant and mammal species globally (Hillman 1986). The BMNP harbours at least 111 or 18.8% of the national endemic flowering plant species (with 10 restricted to the park limits), 20 or 26.5% of the national endemic mammal species and 9 or 53.3%

of the national endemic birds. In addition, on the Bale Mountain endemic plants density is 2.5 taxa per 100 km^2 (Friis et al. 2005).

Vegetation structure and composition differ between the southwestern and northeastern gradients. On the southwestern transect the vegetation changes from moist tropical rainforest at 2000m asl (altitude of our lowest sampled plot) to broadleaf evergreen forest at around 2800m, to ericaceous forest around 3200m asl, ericaceous shrubland between 3600m and 4100m asl and finally to the Afroalpine shrub and grassland habitat at the Sanetti plateau. On the northeastern transect, the area south of Goba around 2700m asl is dominated by small rainfed agriculture, heavy livestock grazing and browsing grassland and shrublands, and vast plantation of exotic tree species such as Eucalyptus and Cypresses. From 2800m asl first isolated remnant of *Juniperus procera*, *Hagenia abyssinica* and *Hypericum revolutum* and Hypericum woodlands with bushy understories of *Rosa abyssinica* and different species of *Solanum (S. anguivi and S. nigrum)* can be observed. Those fade over into Ericaceous belt around 3700masl and isolated Erica shrubs at around 4100m asl. The main high elevation plateau is characterised by Afroalpine Dwarf Shrubs and various herbaceous formations. Agricultural land encrauches up to around 3500m asl, small scale Garlic plantation may reach to even higher altitude.

Table 1: Vegetation zones and major habitat types of the Bale Mountain. Overlaps in altitude are explained by differences in slope and aspect (based on Miehe and Miehe 1994; Umer et al. 2007).

№	Cover Classes	Aspect	Altitude	Description
1	**Afroalpine dwarf shrubs and herbs formation**	**S, SW and SE**	**3800-4385m**	Afroalpine vegetation: including the dwarf shrubs *Helichrysum splendidum*, *Alchemilla haumanii*, the Giant Lobelia (*Lobelia rhynchopetalum*), isolated groves of dwarf *Erica trimera up to 4100m asl.*
2	**Tussock grasslands**	**N and NW**	**3800-4050m**	Extensive grasslands: dominated by grasses (*Festuca richardii*) with large number of herbaceous species. Bogs vegetated by *Eriocaulon schimperi* and *Carex monostachya.*
3	**Isolated Erica shrubs**	**S, SW, SE and NW**	**3600–4000m**	*Erica* groves within Afroalpine *Helichrysum* heathland. Frequent bush fires keeping Erica in low (up to 3m), shrubby regeneration phases. *Erica trimera* is restricted to distinct patches or solitary individual shrubs.
4	**Ericaceous Belt**	**S, SW and NW**	**3200 - 3600m**	Forest, thickets and scrublands of *Erica trimera* and E. *arborea* communities. *E. trimera* forms tall trees up to 15m height with abundant epiphytes, especially the moss *Antitrichia curtipendula* and the lichen *Usnea articulata*. Above 3,400m a.s.l., which is the well-marked limit of *Hagenia emergents*, *Erica trimera* canopy height diminishes further and grasses and mosses predominate in the ground layer.
5	**Upper Montane forests**	**N and NW**	**3000 – 3400m**	Dominated by trees such as *Pittosporum viridiflorum, Myrsine melanophloeos, Discopodium eremanthum,*

				and prominent bushes such as *Rosa abyssinica and Solanum garae*. Dispersed individuals of large trees such as *Hagenia abyssinica, Hypericum revolutum,* and *Juniperus procera*.
6	**Bamboo forest**	**S and SW**	**2800 – 3100m**	Dominated by bamboo *Sinarundinaria alpine* or *Arundinaria alpine*.
7	**Juniperus, Hypericum and Hygenia Woodland**	**N, and NE**	**2500 – 3400m**	Mainly dominated by a mixed *Juniperus* forest. *Hagenia* and *Hypericum* zone. It is dominated by 12-18m tall *Hypericum revolutum* and *Rapanea melanophloeos*, accompanied by *Schefflera* and bamboo (*Sinarundinaria alpina*), with *Hagenia abyssinica* up to 25m tall.
8	**Afromontane rainforest**	**S and SW**	**1450 – 3250m**	The rainforest is located mainly at the southern slopes and receives rainfall during more than eight months of a year. It is dominated by *Podocarpus* associated with *Syzygium guineense* and *Aningeria adolfi-friederici*.
9	**Farmland, Settlements and Fragmented Landscape**	**E, NE and N**	**2000-3400**	Highly fragmented landscape characterized by expanding agricultural land, infrastructure and settlements.

2.3 Sampling design

Two floristic inventory transects were established across the elevational gradient along the Goba-Rira-Dolo Mena Road. The southwestern transect reached from the humid tropical rain forest to the summit at mount Tullu Demtus 4385m asl, with the northeaster transect approach the summit on the other slope. Starting at 2000m asl, nested circular plots of 20m (1256m^2) and 40m (5024m^2) radii were established along the Southwestern (19 plots) and Northeaster (13 plots) transect of Massif, and all the way up to the summit at every 250 to 300m altitude difference. Presence absence data of all vascular plants in each plot were collected. In addition, plot dominant cover type was visually estimated.

Three replicated plots were established per elevation level following guidelines for optimal sampling along environmental gradients (Schweiger et al. 2016). We used the same approach (same size of sampling plots, at least 500m apart and same duration of surveys) across elevations, zonal habitats and mountain ranges. Prior to vegetation sampling, a reconnaissance survey was carried out along the sampling transect to decide on potential plot locations. Plot's location selection and establishment were carried out randomly after visually judging the environmental. Areas of less disturbance, accessible, slope less than 25° were selected. All plots avoided settlements, roads, plantations, farmland, and logging site.

The field data collection was carried out in April 2011. Altogether, 448 different plant species of 89 families of 6 functional groups were collected. Most species were identified on the spot, with few critical species being pressed and taken to the National Herbarium of Ethiopia located at Addis Ababa University for further identification. The nomenclature and functional group classification follow published flora of Ethiopia and Eritrea (Hedberg and Edwards 1989, 1995; Edwards et al. 1995, 1997 and 2000; Hedberg et al. 2003 and 2004 and Puff and Nemomissa 2005). All the recorded flowering plant species were classified as non-endemics (plants that are common all-over east Africa and the rest of the world), Ethiopian endemics, and Bale endemic (i.e. of course these are Ethiopian endemics but are exclusively found only in the Mountains area).

Altitude, ground position and geographic location of each plot were recorded using Garmin Global Positioning System (GPS) 3.1. Slope and aspect information was derived from Digital Elevation Models (DEMs) (Jarvis 2008). Along altitudinal gradient temperature is the most determinant factor (Beierkuhnlein 2007; Körner et al. 2007, 2011; Nagy and Grabherr 2009). Therefore, for this analysis we focus primarily on temperature and less so on the effects of other environmental variables.

For the estimation of climate change impacts, we assumed 2°C, 3°C and 4°C change, which fall within the Intergovernmental panel on Climate Change (IPCC) optimistic to pessimistic scenarios of the 21st century The IPCC has stated that "warming of the climate system is unequivocal, it will result in above average warming of waterbodies (sea, ocean and snow), air and land surface warming." More specifically, the 21st century climate change induced warming is likely to exceed 1.5°C relative to the 1850 – 1900 period in all scenarios and exceeds 2°C in many scenarios (IPCC 2014).

2.4 Statistical analysis

Overall richness as well as number of Ethiopian (national) and Bale Mountain (local) endemics were calculated for each plot. Generalized Linear Models (GLMs) were used to analyze the relationship between these richness indices as well as percentages of endemic species with elevation. To allow non-linear relationships, the full models included elevation and elevation^2 as explanatory variables.

$$\boxed{\textbf{model formula: } y \sim \text{elevation} + \text{elevation}^2 + \text{transect} + \text{transect: elevation}}$$

Stepwise model selection based on Akaike information criterion (AIC) was used to remove non-relevant variables from the model (R-function *step* in the *stats* package). Poisson error distribution (log-link function) was implemented for all richness-based indices, while binomial error distribution (logit-link function) was used to assess changes in percentage values. The binomial error distribution for percentage values has the advantage that it accounts for the number of observations (i.e. species) that underlies a specific percentage value.

Prior to data analysis the full natural elevational ranges of each species (upper and lower limits of occurrence range) and endemism of all the species were derived from all eight volumes of Flora of Ethiopia and Eritrea books (Hedberg and Edwards, 1989 and 1995; Edwards et al., 1995, 1997 and 2000; Hedberg et al., 2003 and 2004; and Plants of the Semen Mountains, Puff and Nemomissa 2005). In addition, plot occurrence data was used to extract local occurrence range of each species. Information on species range distributions were used to estimate potential consequences of warming induced shifts under different climate change scenarios. We calculated the potential species altitudinal range shift for each species applying a laps rate of 0.6ºC per 100 m of elevation. All statistical analyses and visualisations were performed in R version 3.3.3 (R Development Core Team, 2017).

3. Results

3.1 Gradients of plant species richness

Out of the overall 448 identified vascular plant species, 114 species are endemic to Ethiopia, of which 27 species are Bale mountain area endemic. Species richness showed a significant ($p<0.001$) mid elevation richness peak at around 2800m asl on the southwestern and at 3500m asl on the northerneastern transect (Fig. 2a). After reaching a peak at mid altitude, overall richness decreases slowly towards the summit. Endemic richness per plot showed significant differences between transects, slightly lower on the northeaster transect and increased on the more humid southwestern transect ($p < 0.01$). However, it has shown significant increase with altitude. Endemics richness peaked at higher elevations for both transect (Fig. 2b and c; $p<0.001$, Table 2).

The percentage of endemic species increased with elevation for Ethiopian endemics ($p<0.001$; Fig. 2d) as well as for Bale mountain area endemics on the northerneaster transect ($p<0.001$, Fig. 2e) but showed a tendency of reaching a maximum around 3500m asl (towards hump shaped relationship) for the southwestern transect (Fig. 2e). The south-western transect showed on average higher percentage values than the northeaster transect ($p<0.001$, Fig. 2). The percentage of national endemics showed significant increase with elevation for both transects. However, the percentage of Bale endemics shows increase for the Northeaster transect, while it peaked at around 3500m asl for the southwestern transect.

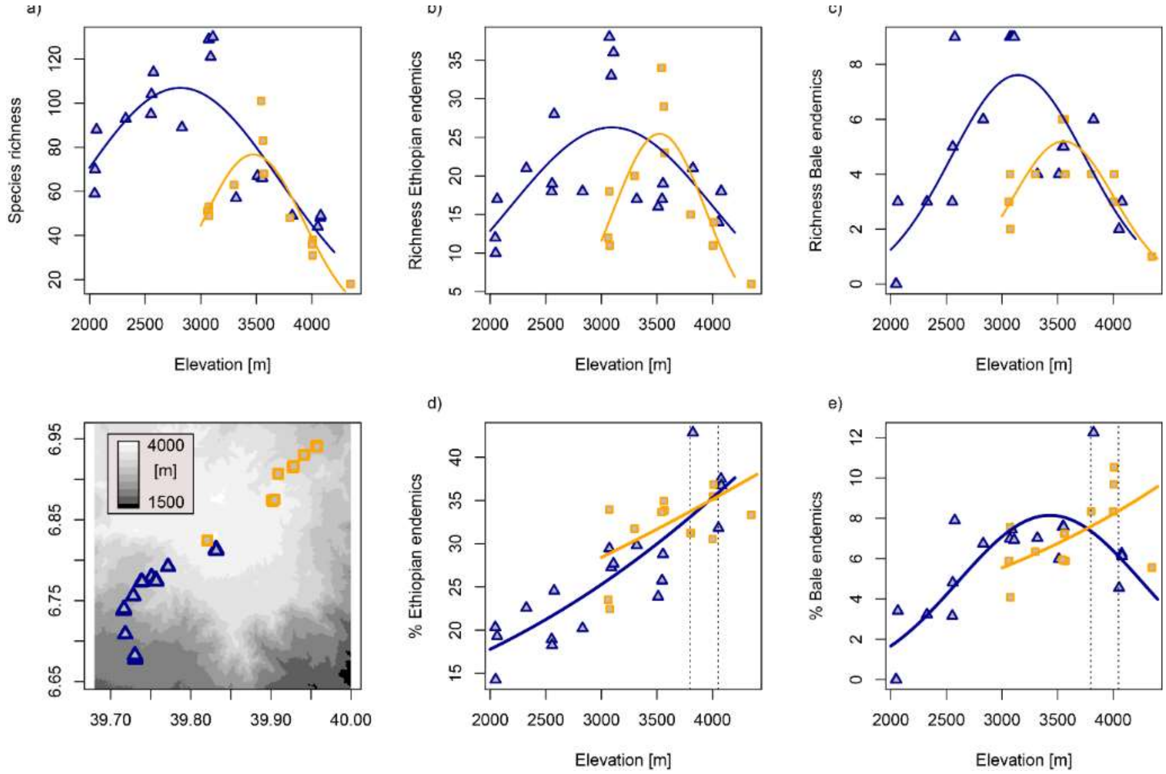

Figure 2: Species diversity and percent endemic species richness along the altitudinal gradient: (a) Overall species richness for both Southwester (blue) and Notheastern (orange) transects. (b) richness of Ethiopian endemics (c) richness of Bale area endemic (d) percent Ethiopian endemics and (e) percent Bale area endemics. The map shows the distribution of sampling plots along elevational gradient on both transects of the study area. Note that the models shown in the figures were fitted independently after separating data from the southern and the northern transect, while the main text reports results of the overall richness model (Table 2 below), exception of the percentage of Bale are endemics (e) where the northern transect shows only a linear fit, results don't differ qualitatively.

3.3 Estimated future altitudinal range shift

When analysing plot species occurrence data (Figure 3a) estimated altitudinal range shifts following temperature increase cause the potential local extinction of 2.1% of all species at 2°C increase. Plants that are threatened with extinction include *Sedium mooney, Anthemis tigreensis, Helichrysum harennensis, Lobelia rhynchopetalum, Minuaritia filitolia, Senecio schimperi, Geranium arabicum Subsp. Pedunculata, Carex simensis, Helichrysum horridium*, and *Senecio inarnatus* of which 6 or one in five are exclusively Bale mountains area endemic. The temperature increases by 3°C to 4°C predicted 8.9% (of 41 species) local extinction of species. When estimating the effect of temperature induced altitudinal range shifts based on the species natural elevational occurrence range reported in the literature (Figure 3b) analyses predict the local extinction of four species (1%: *Senecio schimperi, Festuca richardii, Veronica gunae,* and *Agrostis gracilifollia*) and up to 11.2% or 50 species extinctions due to unavailability of habitat to move to. For a temperature increase of 3°C to 4°C, however this approach predicted larger rate of extinction i.e. up to 60 species (13.4%) and 65 species (14.5%), respectively.

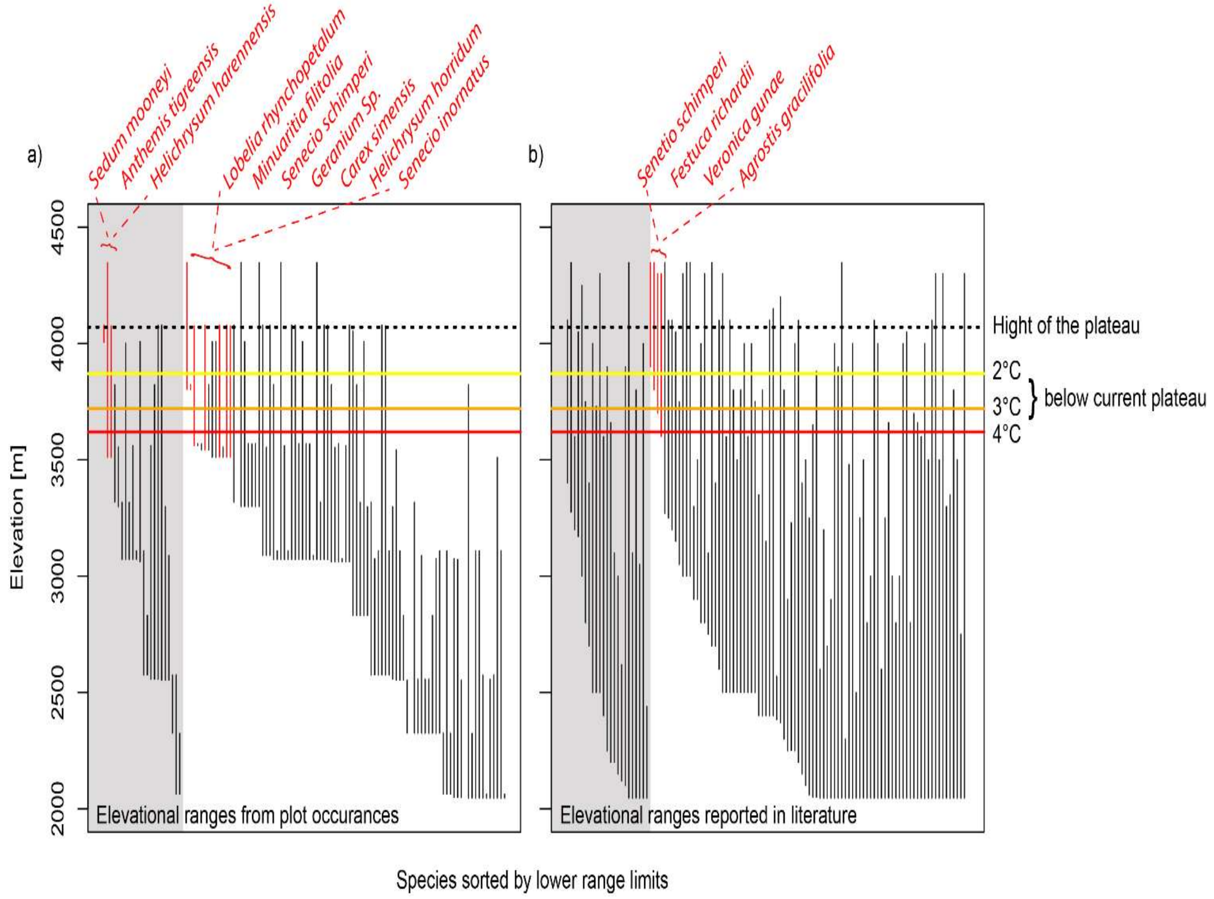

Figure 3: All identified species sorted by lower and upper range limits acquired from plot occurrence data (a) and species documented natural lower and upper range acquired from literature (b). The dashed line indicates maximum elevation of the plateau, beyond which are three emerging small peaks. Those peaks are small in area and are unlikely to sustain independent populations of species. Hence, here marks the elevation of the plateau as a hard boundary for long term species survival. The yellow (2^0C), orange (3^0C) and red (4^0C) lines indicate a shift in elevation caused by temperature. Red species ranges loose at least 90% of their current range by the expected temperature increase (4^0C).

Table 2: Best models after stepwise model selection (based on AIC). E: elevation, T: transect (souths)

Dependent variable	*Best model formula after stepwise model selection*	*Error distributio*
Richness	$-3.3\pm0.9\ (p<0.001) + 4.6\text{x}10^{-3}\pm0.5\text{x}10^{-3} * E\ (p<0.001) - 7.1\text{x}10^{-7}\pm0.7\text{x}10^{-7} * E^2\ (p<0.001) + 2.3\pm0.5 * T\ (p<0.001) - 5.7\ \text{x}10^{-4}\pm1.4\text{x}10^{-4} * E{:}T\ (p<0.001)$	Poisson (log-link
Number of Ethiopian endemics	$-5.3\pm1.8\ (p<0.01) + 4.9\text{x}10^{-3}\pm1.0\text{x}10^{-3} * E\ (p<0.001) - 7.3\text{x}10^{-7}\pm1.3\text{x}10^{-7} * E^2\ (p<0.001) + 1.6\pm8.6 * T$ (non sig.) $- 4.0\ \text{x}10^{-4}\pm2.4\text{x}10^{-4} * E{:}T$ (non sig.)	Poisson (log-link
Number of Bale Mountains area endemics	$-16.7\pm4.3\ (p<0.001) + 1.0\text{x}10^{-2}\pm0.2\text{x}10^{-2} * E\ (p<0.001) - 1.5\text{x}10^{-6}\pm0.3\text{x}10^{-6} * E^2\ (p<0.001) + 4.3\pm2.0 * T\ (p<0.05) - 1.1\ \text{x}10^{-3}\pm0.6\text{x}10^{-3} * E{:}T\ (p<0.05)$	Poisson (log-link
% Ethiopian endemics	$-2.4\pm0.3\ (p<0.001) + 4.7\text{x}10^{-4}\pm0.8\text{x}10^{-4} * E\ (p<0.001)$	Binomial (logit-l
% Bale Mountains area endemics	$-9.9\pm2.7\ (p<0.001) + 4.1\text{x}10^{-3}\pm1.7\text{x}10^{-3} * E\ (p<0.05) – 5.7\text{x}10^{-7}\pm2.7\text{x}10^{-7} * E^2\ (p<0.05)$	Binomial (logit-l

4. Discussion

4.1 Vegetation zonation and plant species diversity and distribution

Our field data revealed a hump shaped pattern (i.e. diversity peaks at intermediate elevations) for overall species and endemic richness in the Bale mountains as well as increasing numbers of endemic towards the Afroalpine plateau. These result mirror similar patterns observed in other Ethiopian mountain (Wana and Beierkuhnlein 2010) and are also common in mountains globally (Bruun et al. 2006; Lomolino 2001; Steinbauer et al. 2016a). Simulations have shown that a hump-shaped pattern of species richness could result from a random placement of species' geographical ranges along a gradient with hard boundaries (such as elevation, temperature etc; Grytnes 2003). Mid elevation peaks in species density or diversity may also be caused by reoccurring elevation altitudinal range shifts, when the uppermost and lowermost species face higher extinction risks during environmental fluctuations (Lomolino 2001).

One of the most important factors defining species richness is area (species-area relationship; Würtz and Annila 2008). The decline in are with elevation found on conical mountains supports a steady decline in species richness. In contrast, the presence of the high elevation plateau in the Bale mountains would favour a richness peak at high elevations. Such area effect are unlikely to directly affect the observed mid elevation richness peak in our analyses as the area of the elevational belts with highest diversity is not particularly large. It is more likely that vegetation dynamics following historic climate changes may have contributed to shape current diversity patterns.

Our finding is in line with a recent diversity analysis across ecosystems in Ethiopia explaining the exceptional diversity with the presence of high diversity of trees, shrubs and herbs across all ecosystems of the country as compared to more specialised succulents, grasses, climbers, lianas, epiphytes and geophytes (Lemessa and Teka 2017). We further speculate that orography related precipitation effects and resources diversity may influence the current diversity pattern. Precipitation is higher in mid-elevations when compared to the flat alpine plateau (Hillman 1986). In addition, the topography of the steeper slopes may cause small-scale climatic heterogeneity allowing the coexistence of species with differing environmental tolerances in smaller areas when compared to the relatively flat plateau (Diamond 1988, Winkler et al. 2016). The steep slopes may also shelter plant species from the large density of natural and domestic herbivores which particularly are affecting the flat plateau area (Irl et al. 2014).

Endemic richness was found to reach its maximum in higher elevations than overall richness likely reflecting the in-situ evolution of novel species in isolated high-elevation habitats of Afroalpine mountains (Steinbauer et al. 2013). The resulting increase - or high elevated peak - in the percentage of endemic species is consistent with similar patterns on other tropical mountains (Mallet-Rodrigues et al. 2010; Jump et al. 2012; Nogué et al. 2013) and reported from mountains on oceanic islands (Steinbauer et al. 2012). Therefore, the term “sky islands” has been coined to reflect the island-like character of tropical alpine mountains (Irl and Beierkuhnlein 2011). An increase in ecological isolation with elevation promotes isolation driven speciation and thus higher rates of evolutionary activity (Steinbauer et al. 2016a). In line with this phylogenetic evidence across the globe indicate that many high-elevation endemics are phylogenetically young taxa resulting from fast diversification (Hutter et al. 2013; Salerno et al. 2012; Merckx et al. 2015). The Bale Mountains Afroalpine ecosystems are geographically isolated patches among the mountains along the Great Rift Valley. The high elevation and unique topography of these mountains disconnects them from the rest of east African mountains causing considerable geographically isolation from neighbouring mountains and landscapes. High altitude related strong environmental filters enable unique and specialized species to survive under such harsh conditions, which favours endemism over long evolutionary times.

Adding to the effect of largescale isolation, orography causes considerable small-scale differences in environmental conditions promoting environmental heterogeneity and thus the coexistence of a high diversity of species. The mountains receive high amount of rainfall differing considerably between the south-western and the north-eastern transects. Hence, over time different pools of species adapted to different microclimatic condition have evolved. We found considerable differences in species richness, but also in the spatial patterns of diversity along elevation on alternating sites of the mountain's slopes.

While Bale Mountains have always been inhabited by humans, the recent population growth and intensification of activities influence the distribution of species (i.e. domestic animal grazing, fire, expansion of agricultural land, deforestation, overgrazing, and unmanaged settlement). Burgess et al. (2007), found strong positive correlation between human density and local species richness, the number of endemic species and the density of threatened species across the three tropical African mountain ranges, and all sub-Saharan Africa. While a positive relationship between human density and species richness may partly be explained by a biased species sampling (Barbosa et al. 2010; Barbosa et al. 2013), this may also mirror the focus of human activities on productive, often diverse sites as well as the ecosystem services which highly diverse ecosystems provide for human livelihood. Particularly the increase in the percentage of threatened species with human settlement density is of major concern for future development in the Bale mountains where human settlement activity has increased considerable in recent years. While across most high mountain ranges anthropogenic disturbance usually declines with increasing elevation and isolation, recent development suggests intensifying human disturbance in high elevation sites of the Bale mountains. Raising temperatures are expected to make the high elevation plateau of the Bale Mountains even more suitable for human land use. The increasing and more frequent domestic stock grazing on the Afroalpine zone may be a first sign of this climate driven land use change. While the Afroalpine plateau has traditionally been used only for pastoral activities, year-round grazing is becoming increasingly common. These challenges are not restricted to the Bale mountains but threat on unique diversity in all African tropical mountains, which are increasingly populated by dense and poor rural population with livelihood strategies largely relying on farming (Burgess et al. 2007).

Fire is another important factor affecting plant species composition across the massive. The entire Bale Mountains massif, the high-altitude belt but to a lesser extent also Harenna Forest, is affected by recurrent fires which often significantly threaten local biodiversity and key habitats (Wesche et al. 2000; Johansson et al. 2012).

4.2 Ppotential altitudinal range shift and local extinction

Our climate projections indicate that climate change induced warming may have far reaching impact on the Afroalpine plants. Many Afroalpine species face their uppermost range boundaries above the plateau limit and are expected to suffer from range losses and potential extinction. Our estimates predicted potential species extinction even under the uninventable warming scenario of a 2°C temperature increase. Mountain top extinction is a substantial concern for endemic species lacking disjunct populations elsewhere on higher mountains or at cooler latitudes (Lenoir et al., 2010). In the Bale mountain, particularly the national and Bale area endemic species are highly endangered than others. Our results mirror similar studies on the impacts of climate change on the natural systems of Guhe mountains of Ethiopia (Kryling et al. 2010). The results also reflect in more advanced modelling approaches for single species, like the endemic *Lobelia rhynchopetalum*, for which extinction in Bale mountains and Semen Mountains is predicted based on large number single species observations covering a large area (Chala et al. 2016).

Accelerated climate change effects observed in better studied mountain regions (Steinbauer et al. 2018) would particularly affect plants that are unable to adapt to the rapidly changing climate or with limited potential to move their occurrence range. This likely includes many of the Afroalpine specialist that are adapted to the intense daily cycles including freezing night temperatures. With climate changing, these adaptations are less relevant making the native flora susceptible to completion by newly established species.

Besides range contraction and habitat loss climate change induced warming may also result in increased susceptibility of vascular plants to pests and diseases, effect on carbon sequestration, and other far reaching genetic and evolutionary implications (Jump et al. 2009). Even species persisting in fragmented localities due to high phenotypic plasticity and present microclimatic refugia may face a decline in their genetic diversity endangering the long-term viability of their populations (Struebig et al. 2011).

Climate change may even result in fundamental ecosystems transformations or collapse, hence a change or loss in species functionality. With climate change induced thermal isotherms shift, dominant thermophilus plant species such as Erica will be able to establish and transform ecosystems on the plateau. Historical records indicate that Erica may have been dominating the alpine plateau during warm phases just after the start of the Holocene, around 11,200 cal BP (Kuzmicheva et al. 2013). Erica is currently distributed all over the massive between 3200 - 4200m asl with growth form ranging from tall tree of up to 12m to small dwarf shrubs. The potential effects of a new dominant species establishing on the plateau demand further investigations.

Conclusions

Our analysis indicates that the plant species diversity around the Bale Afroalpine ecosystem is rich and the area harbours exceptional concentrations of endemic species. The Mountains ecosystem and adjacent tropical mountain rainforest forests harbours exceptional high numbers of endemic plants and animals. Despite, the wide recognition of the area as the world's greatest biodiversity hotspot, the commitment to give the area international recognition, conservation management support, and protection seem to be delayed.

Currently, the natural habitat is under threat from climate change and immediate human activities. Warming-induced thermal isotherm shift will compel plants to either move, adapt or face extinction. Our findings provide evidence that climate change endangers a significant part of the unique Afroalpine flora. Intensified land use activities may further exacerbate the situation.

Conservation management strategies need to address these novel challenges within the areas of the national park and include the buffer zone around the boundaries and subzones surrounding the national park. Effective strategies need to acknowledge local people and their socio-economic situation. The intensified grazing driven by a larger number of domestic animals, large-scale land grabbing, and agricultural expansion are realities that need to be studied and addressed in efficient conservation planning.

To date, climate change impacts on the biodiversity, the Afroalpine endemics, and the ecosystem services of the Bale mountains are not well studied. Scientific investigation and predictions on the complex interactions between biota (i.e. competition, priority effects, etc.) and climate change are urgently needed for this sky island system along with ecological studies that consider human population and socioeconomic growth, and its impacts on the ecosystem in the face of climate change.

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References

Barbosa, A.M., Real, R., and Vargas, J.M., 2010. Use of Coarse-Resolution Models of Species' Distributions to Guide Local Conservation Inferences. Conservation Biology. 24 (5), 1378–1387. DOI: 10.1111/j.1523-1739.2010.01517.x.

Barbosa, A.M., Real, R., Roman Munoz, A., and Brown, J.A., 2013. New measures for assessing model equilibrium and prediction mismatch in species distribution models. Diversity and Distributions. 19, 1333–1338. DOI: 10.1111/ddi.12100.

Bhattarai, K.R. & Vetaas, O.R. 2003. Variation in plant species richness of different life forms along a subtropical elevation gradient in the Himalayas, east Nepal. Global Ecology and Biogeography 12: 327–340.

Beierkuhnlein C. 2007. Biogeografie. Die räumliche Organisation des Lebens in einer sich verändernden Welt, Eugen Ulmer Verlag, Stuttgart, Germany.

Bonnefille, R.,1983. Evidence for a cooler and drier climate in the Ethiopian uplands towards 2.5 Mys ago. Nature. 303, 487-491. doi:10.1038/303487a0.

Bruun, H.H., Moen, J., Virtanen, R., Grytnes, J.A., Oksanen, L. and Angerbjorn, A., 2006. Effects of altitude and topography on species richness of vascular plants, bryophytes, and lichens in alpine communities. Journal of Vegetation Science. 17, 37–46. DOI: 10.1111/j.1654-1103.2006.tb02421.x.

Burgess, N.D., Balmford, A., Cordeiro, N.J., Fjeldsa, J., Kuper, W., Rahbek, C., Sanderson, E.W., Scharlemann, J.P.W., Sommer, J.H. and Williams, P.H., 2007. Correlations among species distributions, human density, and human infrastructure across the high biodiversity tropical mountains of Africa. Bioliological Conservation. 134, 164-177. Doi: 10.1016/j.biocon.2006.08.024

Buytaert, W., Cuesta-camacho, F. and Tobon, C., 2011. Potential impacts of climate change on the environmental services of humid tropical alpine regions. Global Ecology and Biogeography. 20, 19-33. DOI: 10.1111/j.1466-8238.2010.00585.x.

Chala, D., Brochmann, C., Psomas, A., Dorothee Ehrich, D., Gizaw, A., Masao, C. A., Bakkestuen, V., Zimmermann, N. E., 2016. Good-bye to tropical alpine plant giants under warmer climates? Loss of range and genetic diversity in Lobelia rhynchopetalum. Ecology and Evolution. 6, 8931-8941. DOI: 10.1002/ece3.2603.

Diamond, J., 1988. Factors controlling species diversity: overview and synthesis. Annals of the Missouri Botanical Garden. 75(1), 117-129. doi:10.2307/2399469.

Davis, M. B., Shaw, R. G., and Etterson, J. R., 2005. Evolutionary responses to changing climate. Ecology. 86 (7), 1704-1714. DOI: 10.1890/03-0788.

Dullo, B. W., Grootjans, A. P., Roelofs, J. G. M., Senbeta, A. F., & Fritz, C., 2015. Fen Mires with cushion plants in Bale Mountains, Ethiopia. *Mires and Peat. 15*, 1-10.

Edwards, S., Mesfin, T., and Hedberg, I., (eds), 1995. Flora of Ethiopia and Eritrea. Vol. 2, No. 2 The National Herbarium, Addis Ababa and Department of Systematic Botany, Uppsala, Sweden.

Edwards, S., Mesfin, T., and Sebsebe, D., (eds)., 2000. Flora of Ethiopia and Eritrea. Vol. 2, No. 1 The National Herbarium, Addis Ababa and Department of Systematic Botany, Uppsala, Sweden.

Edwards, S., Sebsebe, D., and Hedberg, I., (eds)., 1997. Flora of Ethiopia and Eritrea. Vol. 6, The National Herbarium, Addis Ababa and Department of Systematic Botany, Sweden.

Enquist, C.A.F., 2002. Predicted regional impacts of climate change on the geographical distribution and diversity of tropical forests in Costa Rica. Journal of Biogeography. 29, 519-53

Friis, I., 1992. Forests and forest trees of northeast tropical Africa. Their natural habitats and distribution patterns in Ethiopia, Djibouti, and Somalia. Kew Bull Additional Series 15, HMSO, London.

Friis, I., Thulin, M., Adsersen, H., and Burger, A.M., 2005. Patterns of plant diversity and endemism in the Horn of Africa. Biol. Skr. 55, 289 - 314. ISSN 0366-3612. ISBN 87-7304-304-4.

Gehrke, B., and Linder, H.P., 2014. Species richness, endemism, and species composition in the tropical Afroalpine flora. Alp Botany. 124, 165-177. DOI: 10.1007/s00035-014-0132-0.

Grytnes, J.A., 2003. Species-richness patterns of vascular plants along seven altitudinal transects in Norway. Ecography. 26, 291-300.

Grytnes, J.A., and McCain, C.M., 2007. Elevational trends in biodiversity. S.A. Levin (Ed.), Encyclopedia of Biodiversity, Elsevier Inc. 1-8. DOI: 10.1016/B978-012226865-6/00503-1.

Hedberg, I., and Edwards, S., (Eds.)., 1989. Flora of Ethiopia: Pittosporaceae to Araliaceae. Vol. 3, The National Herbarium, Addis Ababa and Department of Systematic Botany, Uppsala. Sweden

Hedberg, I., and Edwards, S., (Eds.)., 1995. Flora of Ethiopia and Eritrea. Vol. 7, The National Herbarium, Addis Ababa and Department of Systematic Botany, Uppsala, Sweden.

Hedberg, I., Edwards, S., and Sileshi, N., (Eds.)., 2003. Flora of Ethiopia and Eritrea. Vol. 4, No. 1 The National Herbarium, Addis Ababa and Department of Systematic Botany, Uppsala, Sweden.

Hedberg, I., Friis, I., and Edwards, S., (Eds.)., 2004. Flora of Ethiopia and Eritrea. Vol. 4, No. 2 The National Herbarium, Addis Ababa and Department of Systematic Botany, Uppsala, Sweden.

Hedberg, O., 1951. Vegetation belts of the East African mountains. Svensk Botanisk Tidskrift. 45, 140 – 202.

Hedberg, O., 1964. Features of Afroalpine plant ecology. Acta Phytogeographica Suecica. 49, 1-144.Hillman, J.C. 1986. Conservation in Ethiopia's Bale Mountains. Endangered Species. 3, 1-4.

Hillman, J.C., 1988. The Bale Mountains National Park area, southeast Ethiopia and its management. Mountain Research and Development. 8, 253-258.

Hulme M., Doherty, R., Ngara, T., New, M., and Lister, D., 2001. African climate change: 1900–2100. Climate Change Research. 17: 145–168. doi:10.3354/cr017145.

Hutter, C.R., Guayasamin, J.M., and Wiens, J.J., 2013. Explaining Andean megadiversity: the evolutionary and ecological causes of glass frog elevational richness patterns. Ecology Letters. 16, 1135-1144. DOI: 10.1111/ele.12148.

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151.

Irl, S., Steinbauer, M., Epperlein, L., Harter, D., Jentsch, A., Pätz, S., Wohlfahrt, C., Beierkuhnlein, C., 2014. The hitchhiker's guide to island endemism - biodiversity and endemic perennial plant species in roadside and surrounding vegetation. Biodiversity and Conservation. 23, 2273 – 2287. doi: 10.1007/s10531-014-0722-6.

Irl, S.D.H. and Beierkuhnlein, C., 2011. Distribution of endemic plant species on an oceanic island – a geospatial analysis of La Palma (Canary Islands). Procedia Environmental Sciences. 7, 170-175. DOI: 10.1016/j.proenv.2011.07.030.

Itescu, Y., 2018. Are island-like systems biologically similar to islands? A review of the evidence. Ecography. 42, 1-17. DOI: 10.1111/ecog.03951.

Jarvis, A., Reuter, H.I., Nelson, A., Guevara, E. Hole-Filled SRTM for the Globe Version 4, available from the CGIAR-CSI SRTM 90m Database. Available online: http://srtm.csi.cgiar.org (accessed on 5 July 2018).

Jacob, M., Annys, S., Frankl, A., De Ridder, M., Beeckman, H., Guyassa, E., and Nyssen, J., 2014. Treeline dynamics in the tropical African highlands identifying drivers and dynamics. Journal of vegetation science. 26, 9-20. DOI: 10.1111/jvs.12215.

Jentsch, A., and Beierkuhnlein, C., 2003. Global climate change and local disturbance regimes as interacting drivers for shifting altitudinal vegetation patterns. Erdkunde 57: 216–231.

Johansson, M. U., Fetene, M., Malmer, A., and Granström, A., 2012. Tending for cattle: traditional fire management in Ethiopian montane heathlands. Ecology and Society. 17(3), 19. DOI: 10.5751/ES-04881-170319.

Jump, A.S., Huang, T.J., Chou, C.H., 2012. Rapid altitudinal migration of mountain plants in Taiwan and its implications for high altitude biodiversity. Ecography. 35, 204-210. DOI: 10.1111/j.1600-0587.2011.06984.x.

Jump, A.S., Matyas, C., and Penuelas, J., 2009. The altitude-for-latitude disparity in the range retractions of woody species. Trends in Ecology and Evolution. 24, 694-701. DOI: 10.1016/j.tree.2009.06.007.

Kidane, Y., Stahlman, R., and Beierkuhnlein, C., 2012. Vegetation dynamics, and land use and land cover change in the Bale Mountains, Ethiopia. Environ Monitoring Assessment. 184(12), 7473-7489. doi: 10.1007/s10661-011-2514-8.

Körner, C., Jetz, W., Paulsen, J., Payne, D., Rudmann-Maurer, K., Spehn, E.M., 2017. A global inventory of mountains for bio-geographical applications. Alpine Botany. 127, 1-15. doi:10.1007/s00035-016-0182-6.

Körner, C., 2007. The use of 'altitude' for ecological research. Trends in Ecology and Evolution. 22 (11), 569-574. DOI: 10.1016/j.tree.2007.09.006.

Kreyling, J., Wana, D., and Beierkuhnlein, C., 2010. Climate warming and tropical plant species - consequences of the potential upslope shift of isotherms in southern Ethiopia. Diversity and Distribution. 16, 593-605. DOI: 10.1111/j.1472-4642.2010.00675.x.

Kuzmicheval, E. A., Debella, H., Khasanov, B., Krylovich, O., Babenko, A., Savinetsky, A., Severova, E., and Yirga S., 2013. Holocene hyrax dung deposits in the Afroalpine belt of the Bale Mountains (Ethiopia) and their palaeoclimatic implication. Journal of Environmental Archaeology. 18 (1), 72-81. DOI: 10.1179/1461410313Z.00000000018.

Kuzmicheval, E. A., Khasanov, B.F., Krylovich, O. A., and Savinetsky, A.B., 2014. Vegetation and Climate Reconstruction for the Bale Mountains (Ethiopia) in the Holocene According to the Pollen Analysis and Radiocarbon Dating of Zoogenic Deposits. 458 (1), 116-121. DOI: 10.1134/S0012496614050019.

Lemessa, D., and Teka, Y., 2017. Patterns of the Diversity of Characteristic Species Across Vegetation Ecosystems of Ethiopia. Ecology and Evolutionary Biology. 2(3), 34-44. DOI: 10.11648/j.eeb.20170203.11

Lenoir, J., Gégout, J. C., Guisan, A., Vittoz, P., Wohlgemuth, T., Zimmermann, N. E., Svenning, J. C., 2010. Going against the flow: potential mechanisms for unexpected downslope altitudinal range shifts in a warming climate. Ecography. 33, 295-303. DOI: 10.1111/j.1600-0587.2010.06279.x.

Lomolino, M.V., 2001. Elevation gradients in species density: historical and prospective views. Global Ecology and Biogeography. 10, 3-13. DOI: 10.1046/j.1466-822x.2001.00229.x.

Lomolino, M.V., Pijanowski, B.C., and Gasc, A., 2015. The silence of biogeography. Journal of Biogeography. 42(7), 1-10. doi:10.1111/jbi.12525

Lovejoy, T., 2008. Climate Change and Biodiversity. Rev. sci. tech. Off. int. Epiz. 27(2), 331-338.

Malcolm, J.R., Liu C., Neilson, R.O., Hansen, A., and Hannah, L., 2006. Global Warming and Extinctions of Endemic Species from Biodiversity Hotspots. Conservation Biology. 20(2), 538-548. DOI: 10.1111/j.1523-1739.2006.00364.x.

Mallet-Rodrigues, F., Parrini, R., Pimentel, L.M.S. and Bessa, R., 2010. Altitudinal distribution of birds in a mountainous region in southeastern Brazil. Zoologia. 27, 503–522. DOI: 10.1590/S1984-46702010000400003.

Merckx, V.S.F.T., Hendriks, K.P., Beentjes, K.K., Mennes, C.B., Becking, L.E., Peijnenburg, K.T.C.A., Afendy, A., Arumugam, N., et al. 2015. Evolution of endemism on a young tropical mountain. Nature. 524, 347-350. doi:10.1038/nature14949.

Miehe, G., and Miehe, S., 1994. Ericaceous forests and heathlands in the Bale Mountains of South Ethiopia: Ecology and man's impact. Stiftung Waldurhaulting in Afrika. Humburg. Germany.

Mittermeier, R.A., Robles Gil, P., Hoffmann, M., Pilgrim, J., Brooks, T., Mittermeier, C.G., Lamoreux, J., da Fonseca, G.A.B., 2004. Hotspots Revisited: Earth's Biologically Richest and Most Endangered Terrestrial Ecoregions. CEMEX, Mexico City. Mexico.

Mohr, P.A., 1971. The Geology of Ethiopia. 2nd ed. Haile Sellassie I University Press, Addis Ababa. Ethiopia.

Mutke, J., Kier, G., Braun, G., Schultz, Chr., Barthlott, W., 2001. Patterns of African vascular plant diversity: A GIS-based analysis. Systematics and Geography of Plants. 71 (2): 1125-1136. DOI: 10.2307/3668744.

Nagy, L., and Grabherr, G., 2009. The Biology of alpine habitats. Oxford University Press. Oxford.

Nikulin, G., Jones, C., Giorgi, F., Asrar, G., Buchner, M., Cerezo-mota, R., Christensen, O. B., Deque, M., Fernandez, J., Hansler, A., Meijgaard, E.V., Samuelsson, P., Sylla, M.B., and Sushamak, L., 2012. Precipitation Climatology in an Ensemble of CORDEX-Africa Regional Climate Simulations. Journal of Climate. 25, 6057-6078. DOI: 10.1175/JCLI-D-11-00375.1.

Nogué, S., Rull, V., and Vegas-Vilarrúbia, T., 2013. Elevational gradients in the neotropical table mountains: patterns of endemism and implications for conservation. Diversity and Distribution. 19, 676-687. DOI: 10.1111/ddi.12017.

Nogués-Bravo, D., López-Moreno, J.I., and Vicente-Serrano, S. M., 2012. Climate Change and its Impact. Mediterranean Mountain Environments, 1st ed. Edited by Ioannis N. Vogiatzakis. DOI: 10.1002/9781119941156.ch9.

Osmaston, H.A., Mitchell, W.A. and Osmaston, J.A.N., 2005. Quaternary glaciation of the Bale Mountains, Ethiopia. Journal of Quaternary Science. 20, 593-606. doi:10.1002/jqs.931.

Parmesan, C., 2006. Ecological and Evolutionary Responses to Recent Climate Change. Annual Review of Ecology, Evolution, and Systematics. 37, 637-669. DOI: 10.1146/annurev.Ecol Syst. 37.091305.110100.

Peyron, O., Jolly, D., Bonnefille, R., Vincens, A., and Guiot, J., 2000. The climate of East Africa 6000 14 C Yr B.P. as Inferred from Pollen Data. Quaternary Research. 54, 90-101. doi:10.1006/qres.2000.213.

Puff, C., and Nemomissa, S., 2005. Plants of the Simien: A flora of the Simien Mountains and surroundings, northern Ethiopia. Scripta Botanica Belgica. Volum 37. National Botanical Garden. Belgium.

Rahbek, C., 2005. The role of spatial scale and the perception of large-scale species-richness patterns. Ecology Letters. 8, 224–239. DOI: 10.1111/j.1461-0248.2004.00701.x.R Development Core Team., 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

Salerno, P.E., Ron, S.R., Señaris, C., Rojas-Runjaic, F.J.M., Noonan, B.P., and Cannatella, D.C., 2012. Ancient Tepui summits harbor young rather than old lineages of endemic frogs. Evolution. 66, 3000-3013. DOI: 10.1111/j.1558-5646.2012.01666.x.

Sanchez-Gonzalez, A. & Lopez-Mata, L. 2005. Plant species richness and diversity along an altitudinal gradient in the Sierra Nevada, Mexico. Diversity and Distributions 11: 567–575.

Schweiger, A. H., Irl, S.D.H., Steinbauer, M.J., Dengler, J., and Beierkuhnlein, C., 2016. Optimizing sampling approaches along ecological gradients. Methods in Ecology and Evolution. 7, 463–471.

Smith, A.P., Young, T.P., 1987. Tropical Alpine Plants Ecology. Annuals Review of Ecology and Systematics. 18, 137-158. doi.org/10.1146/annurev.es.18.110187.001033

Stattersfield, A.J., Crosby, M.J., Long, A.J., Wege, D.C., 1998. Endemic Bird Areas of the World. Priorities for biodiversity conservation. BirdLife Conservation Series No. 7. BirdLife International, Cambridge, UK.

Steinbauer, M., Irl, S., Beierkuhnlein, C., 2013. Elevation-driven ecological isolation promotes diversification on Mediterranean islands In Acta Oecologica-International Journal of Ecology. 47, 52-56. DOI: 10.1016/j.actao.2012.11.004.

Steinbauer, M., Otto, R., Naranjo-Cigala, A., Beierkuhnlein, C., Fernández-Palacios, J.M., 2012. Increase of island endemism with altitude - speciation processes on oceanic islands in: Ecography. 35, 23-32. doi: 10.1111/j.1600-0587.2011.07064.x.

Steinbauer, M. J., Field, R., Grytnes, J. A., Trigas, P., Ah-Peng, C., Attorre, F., … Beierkuhnlein, C., 2016a. Topography-driven isolation, speciation, and a global increase of endemism with elevation. Global Ecology and Biogeography. 25(9), 1097–1107. DOI: 10.1111/geb.12469.

Steinbauer, M.J., Irl, S.D.H., González-Mancebo, J.M., Breiner, F.T., Hernández-Hernández, R., Hopfenmüller, S., Kidane, Y., Jentsch, A., and Beierkuhnlein, C., 2016b. Plant invasion and speciation along elevational gradients on the oceanic island La Palma, Canary Islands. Ecology and Evolution: 7(2), 771-779. doi: 10.1002/ece3.2640.

Steinbauer, M. J. et al. 2018. Accelerated increase in plant species richness on mountain summits is linked to warming, *Nature*. DOI: 10.1038/s41586-018-0005-6.

Struebig, M.J., Kingston, T., Petit, E.J., Le Comber, S.C., Zubaid, A., Mohd-Adnan, A., and Rossiter, S.J., 2011. Parallel declines in species and genetic diversity in tropical forest fragments. Ecology Letters. 14:582-590. DOI: 10.1111/j.1461-0248.2011.01623.x.

Uhlig, S., and Uhlig, K., 1991. Mountain chronicles. Studies on the altitudinal zonation of forests and alpine plants in the central Bale Mountains, Ethiopia. Mountain Research and Development. 11, 153-256.

Uhlig, S.K., 1990. Mountain forests and the upper tree limit on the Southeastern plateau of Ethiopia. African Mountains and Highlands: Problems and Perspectives (ed. By Messerli, B., and Hurni, H.). 237-248. The African Mountain Association (AMA). Walsworth Press Co., Inc., Missouri.

Umer, M., Lamb, H.F., Bonnefille, R., Lezine, A.M., Tiercelin, J.J., Gibert, E., Cazet, J.P. and Watrin, J., 2007. Late Pleistocene and Holocene vegetation history of the Bale Mountains, Ethiopia. Quaternary Science Review. 26, 2229-2246. DOI: 10.1016/j.quascirev.2007.05.004.

Walther, G.R., Post, E., Convey, P., Menzel, A., Parmesank, C., Beebee, T.J.C., Fromentin, J.M., Hoegh-Guldberg, O., and Bairlein, F., 2002. Ecological responses to recent climate change. Nature. 416, 389-395. doi:10.1038/416389a.

Wana, D. and Beierkuhnlein, C. 2010. Plant species and growth form richness along altitudinal gradients in the southwest Ethiopian highlands. Journal of Vegetation Science. 21, 617-626. .

Wesche, K., Miehe, G. and Kaeppeli, M., 2000. The significance of fire for Afroalpine ericaceous vegetation. Mountain Research and Development. 20, 340-347. https://doi.org/10.1659/0276-4741(2000)020[0340:TSOFFA]2.0.CO;2.

White, F., 1983. The Vegetation of Africa: a descriptive memoir to accompany the UNESCO/AETFAT vegetation of Africa. UNESCO, Paris, FR.

Winkler, M., Lamprecht, A., Steinbauer, K., Hülber, K., Theurillat, JP et al., 2016. The rich sides of mountain summits–a pan-European view on aspect preferences of alpine plants. Journal of Biogeography. 43 (11), 2261 - 2273. DOI: 10.1111/jbi.12835.

Wurtz, P., and Annila, A., 2008. Roots of Diversity Relations. Journal of Biophysics. 2008. 1-8. DOI: 10.1155/2008/654672.

Chapter 4

Synergistic impacts of climate and land use land cover (LULC) change on vascular plants diversity and distribution along the Bale Mountains: *hotpot of Afroalpine biodiversity*

Yohannes O Kidane[1] and Carl Beierkuhnlein[1,2,3]

[1] Department of Biogeography, Bayreuth, University of Bayreuth, Germany
[2] Bayreuth Center of Ecology and Environmental Research (BayCEER), Bayreuth, Germany
[3] Geographical Institute Bayreuth (GIB), Bayreuth, Germany

> *"The pressures we exert on the planet have become so great that scientists are considering whether the Earth has entered an entirely new geological epoch: the Anthropocene or the age of humans. It means that we are the first people to live in an era defined by human choice, in which the dominant risk to our survival is ourselves."*
>
> Achim Steiner

1. Abstract

Tropical Africa's high mountain ecosystems, particularly Afroalpine ecosystems, own unique environmental conditions that make them high sensitivity to environmental change mainly due to the complex topography-driven isolation resulting in narrow climatic gradients and fragmentation. Contemporarily, the unique ecosystems are exposed to the impacts of multiple drivers of terrestrial ecosystem change mainly to that of Land Use Land Cover (LULC) change, climate change, nitrogen deposition, biotic exchange, and elevated carbon dioxide (CO_2) concentration. This study review provides the contributions of the Ph.D. dissertation (Kidane 2022), which contributes to the advancement of the knowledge on the severity of the synergistic impacts of climate and LULC change on Afroalpine ecosystems and the successful protection of the Afroalpine biodiversity of the Bale massif. The research used *in-situ* plot data and *ex-situ* open data sources, state-of-the-art research approaches, and methodologies. It delivers some missing scientific information on climate and LULC change impacts on the massif's ecosystems and recommends conservation management solutions. The dissertation presented results from studies that focus on the past forty years of LULC dynamics of the area that quantify the status of the eleven major landcover classes of the massive, modeled climate change impact on the dominant cover classes of the massif, such as ericaceous vegetation. Finally, it presents a study examining how climate change impacts vascular plant diversity and richness patterns. Overall, the studies included in the dissertation developed innovative research approaches and applied cost-effective and efficient biodiversity monitoring approaches that utilize the vast geospatial data acquired from remote sensing and advanced geospatial analysis tools and techniques. Moreover, the manuscripts use open-source software, and the studies are published in open-access journals. The modeling and other empirical evidence signaled the area is under the synergistic impact of LULC and climate change, especially the Afroalpine and subalpine ecosystems. Our

finding revealed that the once pristine ecosystems have changed from an entirely natural to a more cultural landscape. Unless serious conservation action is taken, these unique ecosystems will be history before long.

Keywords: Climate change, landscape, biodiversity, LULC change, Remote Sensing, biodiversity, Afroalpine, montane ecosystems, tropical mountains

1. Introduction

Tropical Africa's high mountain top ecosystems, Afroalpine ecosystems, are ecologically very far but physically at a walking distance from the surroundings lowlands ecosystems. They occur in isolated patches restricted to the peaks of the high mountains of the East African Rift System (EARS) and Cameron-Nigeria Mountain ranges between the Tropic of Capricorn and Tropic Cancer (Hedberg 1964; Gehrke and Linder 2014). In Afroalpine mountain ecosystems, long spatial isolation and extreme climatic conditions such as low mean temperature, diurnal freeze-thaw cycles, and other energy-related factors lead to the formation of "Sky Island" like ecosystems with uniquely adapted endemics (Hedberg 1951). The steep gradients of temperature and precipitation, and topographic complexity result in many microsites with a range of adjacent thermal niches (Messerli and Ives 1997; Beierkuhnlein 2007), which created favorable conditions for the evolution of unique flora and fauna adapted to the isolated ecosystems (Spehn et al., 2011).

The existing environmental relationships that shape Afroalpine mountain ecosystems' stability and instability are expected to change in response to the synergistic impacts of climate and LULC change on the altitudinal patterns of biodiversity**.** The interrelation between LULC and climate change is discussed in Olson et al. (2008); Lambin et al. (2003); Spehn et al. (2011); Sala et al. (2000) and MEA (2005) identified five, namely: LULC change, climate change, nitrogen deposition, biotic exchange, and elevated carbon dioxide (CO_2), concentration primary drivers of terrestrial biodiversity loss across global biomes. LULC change is the main threat to terrestrial ecosystems locally, followed by climate change and others.

The impacts of global warming will show a distinct geographical pattern with the changes being greater over land, high latitudes, and elevations (Barry and Seimon 2000; Hannah et al., 2002; Lovejoy and Hannah 2005). Recently, global warming impacts have been observed on mountains ecosystems, i.e., surface temperature increase and glacial melting over the last century across global mountains (Barry and Seimon 2000; Hannah et al., 2002; Nogués-Bravo et al., 2012). Glaciers are near extinction in African mountains, e.g., the receding of glaciers in Mount Kilimanjaro (Chan et al., 2008).

Climate change is expected to impact ecosystem's structure and functioning and plant diversity and distribution at all levels from single species to biomes (Malcolm et al., 2006; Lovejoy 2008). Recently, global biomes have been subjected to the synergistic impact of different drivers of terrestrial ecosystem changes (e.g., Sala et al., 2000; Olson et al., 2001; MEA 2005), mainly climate and LULC change. In mountain ecosystems, climate change will result in the displacement of ecosystem boundaries and a reduction in the total area of the Afroalpine habitat (Kidane et al., 2019; Pihl et al., 2019). Warming will lead to habitat degradation, deterioration, instability, alteration, and modification at all levels of life's organization. Rahbek et al. (2019) further warn that the role of mountains as refugia for biodiversity may come under threat with recent climate change.

The global mean temperature has been rising at 0.25°C per decade, and over the last fifty years, it has increased by around 0.74°C (Colwell et al., 2008; IPCC 2014) of Earth's maximum temperature in the past million years, exceeding the Holocene maximum (9000 to 5000 yr BP) of the current interglacial (Hansen et al., 2006). IPCC (2018) estimated approximately 1.0°C of global average above pre-industrial levels, likely ranging from 0.8°C to 1.2°C. Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate. Nsengiyumva (2021) reviewed the last sixty years' climate change across African mountains and estimated about a 0.278^{0}C increase per decade. Moreover, the rate at which emissions are happening has exceeded that in IPCC baseline scenarios for the present decade (Peters et al., 2012; IPCC 2014).

LULC change studies from the tropical Africa region indicate an intensification of Anthropogenic disturbance since the second half of the 19th century across Afroalpine mountain areas (Burgess et al., 2007). Across ecosystems, LULC change is an essential indicator of biodiversity pattern change (Earn et al., 2000; Röder et al., 2008). In addition, it contributes to climate change indirectly by directly affecting the Earth's radiative forcing and altering the land surface roughness and albedo (Lambin et al., 2003; Röder et al., 2008). It affects sensible heat exchanges, latent heat and carbon dioxide, and other greenhouse gases between the land surface and the atmosphere. Therefore, LULC change monitoring and mitigation are essential for biodiversity conservation and management (Sala et al., 2000; Beierkuhnlein 2002b; Olson et al., 2008).

LULC change is the primary driver of biodiversity patterns change (habitat loss, simplification, niche shrinkage, and fragmentation) at a local scale, which are the leading causes of species extinction (Sala et al., 2000; Beierkuhnlein 2002a; Beierkuhnlein 2002b). Hence, the synergy profoundly impacts biodiversity and the immense ecosystem services they provide (Beierkuhnlein and Jentsch 2005), especially ecosystems and species of marginal areas such as isolated mountain tops, polar regions, and islands (Razgour et al., 2020). Due to climate and LULC change, many species are getting extinct without being noticed or discovered (Malcolm et al., 2006; Kreyling et al., 2010).

The Bale Mountains Afroalpine ecosystems are home to many endemic animals and plants. Thus, they are critically important for biodiversity conservation, particularly the vulnerable wildlife and Afroalpine plant.

Among others, the endemics biota of the Afroalpine habitats is likely to experience unprecedented pressures because of their limited adaptation potential to rapid change and restricted niche with restricted mobility. Therefore, better insight into the current and future processes is necessary to better conservation and manage the Afroalpine ecosystems and sustain their ecosystem services. It is necessary to understand human impact on vascular plant diversity, ecosystem structure and function, species diversity and distribution, endemism, and the underlying environmental processes from landscape to plot and beyond. Especially in remote landscapes of the developing world, knowledge about ongoing processes, though important, is scarce. Hence, developing innovative interdisciplinary research approaches and methodologies on mountain ecosystems is crucial in the face of fast change.

Hence, Afroalpine mountains are suitable for studying change in ecosystem structures and functions in the face of synergistic impacts of climate and Land Use Land Cover (LULC) change. However, research on the synergistic impacts of LULC and climate change on the critical Afroalpine ecosystems is insufficient. The information on a broad range of interactions, including human-biodiversity, species-species, species-functional group, species-ecosystems, lowland-highland relationships, human-natural systems, LULC change, and climate change impacts, and its implication to the Afroalpine biodiversity is far from complete. However, advances in geospatial information acquisition technologies such as remote sensing and advanced computation power, and an increased number of higher education institutes enable better research opportunities.

The Ph.D. dissertation (Kidane 2022) aimed to study the long-term impacts of the main drivers of Afroalpine biodiversity pattern change, especially on the spatial and temporal patterns of vascular plant diversity and distribution. The study mainly focuses on altitudinal gradient analysis, utilizing field sampling and state-of-the-art geospatial information and geospatial analysis tools for climate and LULC change studies. It contributes to the tropical mountains' scientific and empirical knowledge basis by addressing research questions from different biogeographic topics.

The methodologies adopted for the study are suitable for longer-term and broader applications in biodiversity of remote landscape assessment. One of our works (Kidane et al., 2012) has inspired numerous similar spatiotemporal LULC change research in other parts of Ethiopia. Hailu et al. (2018) review Ethiopia's Remote Sensing based LULC products. Of the 146 articles they review, 73% are articles published since 2013 applying similar approaches. However, information on how climate change affects African mountains and its impact on mountain people and ecosystems is limited (Nsengiyumva 2021). The Fifth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) compiled the available knowledge on climate change trends, climate impact and adaptation efforts, and emerging risks in Africa (Niang et al., 2014). The report identified limited information on how climate change affects Afroalpine mountains ecosystems.

The studies included in this review are expected to stimulate research interest in LULC and Climate change impact on Afroalpine mountain ecosystems and, among others, the synergy between the drivers of change. The studies further call on policymakers to incorporate an all-inclusive decision-making process and encourage public debate on the whys and significance of Afroalpine biodiversity conservation. Furthermore, the research aims at raising awareness of contemporary threats to the unique Afroalpine mountain biodiversity in general and Afroalpine flora. It gives insight into incorporating *in-situ* (plot data, ground control points, field research), *ex-situ* (geospatial information from remote sensing and utilizes geospatial analysis tools), and modeling approaches. It shows such resources could improve and support conservation efforts, identify management priorities areas and plan adaptation strategies.

2. Study area

2.1 *Orography*

The research was carried out in the Bale Mountains of Ethiopia, which are home to the most extensive Afroalpine plateau of over 2,600 km^2 in Africa that are home to many uniquely adapted endemic flora and fauna (Hillman 1988; Miehe and Miehe 1994). The vast plateau does not have spacious summits that provide a refugia habitat for an upward shift. The Ethiopian plateau' roof of Africa' rises 1500m asl above the plateau that lies at 2500m asl and comprises 80% of the landmass of Africa above 3000m asl (Monasterio and Vuilleumier 1986). The Bale Mountains are in southeast Ethiopia in the Oromia regional state **(Fig.1)**, between 06°29′N, 39°03′E and 07°10′N, 40°00′E. They support the most extensive Ericaceous vegetation, "the Ericaceous Belt," and are home to one of the last remaining pristine Afroalpine biodiversity hotspots on the continent (Miehe and Miehe 1994; Laurenson et al. 1998). The massif exhibits a steep gradient of ecological zones from tropical rainforests to a midaltitude ericaceous belt that culminates in Afroalpine vegetation. The highest point, mount Tullu Deemtu reaches 4,385 m asl of the massif.

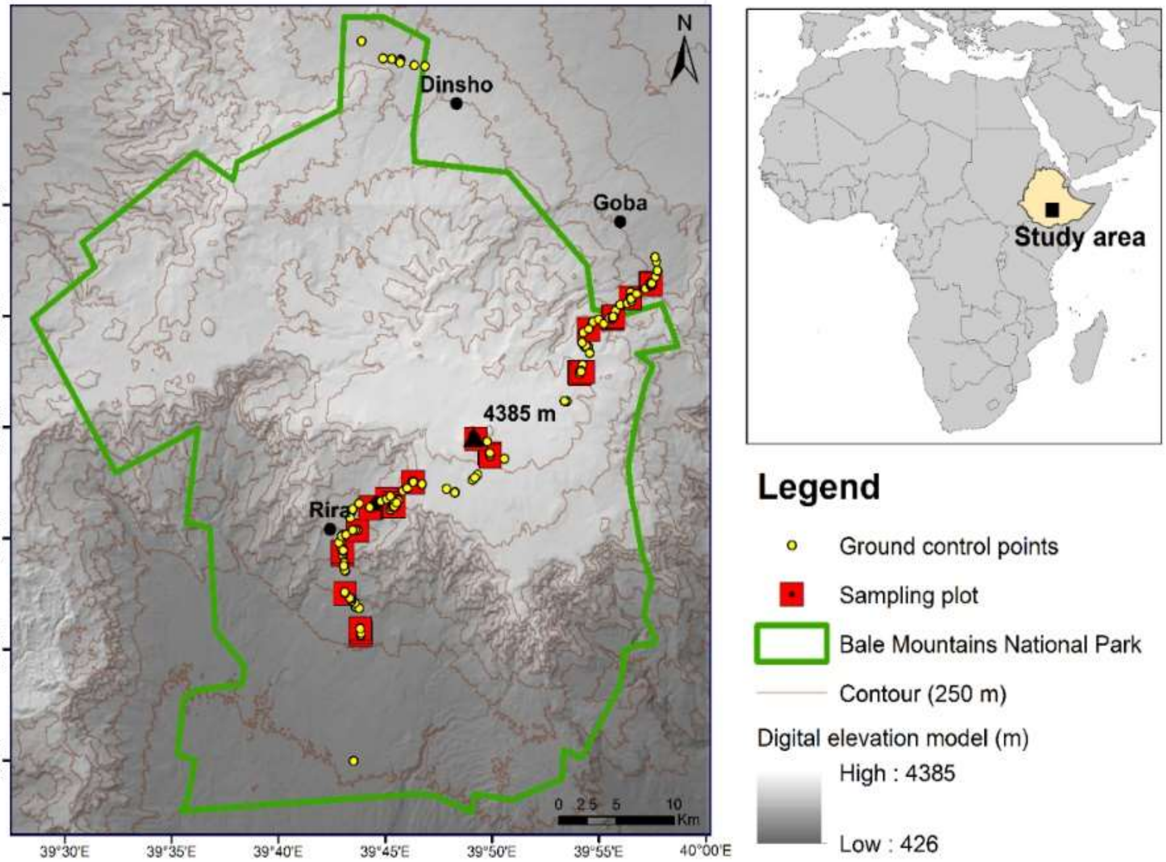

Figure 1: Map of the study area, including the sampling plots transect location, ground control points, and the Bale Mountain National Park (BMNP) boundaries.

2.2 *Climate*

The Bale Mountains are located at the convergence of southeast Ethiopia's wet east and dry northeast African mountains. The climate of the mountains varies from north to south mainly due to the differences in elevation, aspect, and the influences of lowland hot air masses (Uhlig 1990; Uhlig and Uhlig 1991). Historically, the area has experienced a high degree of climate variability and change (Umer et al., 2007; Gil-Romera et al., 2019; Ossendorf et al., 2019). These past climatic changes have played a crucial role in shaping contemporary vegetation. The current climate is characterized by a short dry season (November to February) and a long period of rainfall and high moisture (March to October). The wet season rainfall pattern is slightly bimodal, with a peak from April to May followed by a second peak from September to October (Woldu et al.1989). The area has recently witnessed an increase in the frequency and severity of exceptional droughts (e.g., in 2000, see Wesche 2003).

Rain comes to the Bale Mountains from two different sources: the equatorial westerly and the Indian Ocean monsoon (Uhlig1990; Miehe and Miehe1994). All along altitude, precipitation increases up to an elevation of 3,850 m asl but decreases then again towards the summits (Hillman1986). The northern part of the mountain range exhibits 800 - 1,000 mm of annual rainfall and a wet season from June to September. The southern part is more humid, with a subtropical climate and 1,000 - 1,500 mm of annual rainfall (Woldu et al.1989).

The Afroalpine habitats are characterized by strong diurnal temperature fluctuations and night frost with very low interannual temperature variability (Hedberg 1964; Monasterio and Vuilleumier 1986). One remarkable feature of the Afroalpine climate is its rapid temperature changes (diurnal freeze-thaw cycles and other energy-related factors), primarily due to the thin atmosphere with low heat capacity, intense insolation, and outward radiation due to the changeable cloudiness (Hedberg 1964). On the Sanetti Plateau, Hillmann (1990) recorded extremes of a diurnal temperature range of 40°C (−15°C to +26°C) during the dry season. The diurnal amplitude in temperature varies between the wet and dry seasons. The wet season is warmer at night and cooler by day than the dry season (Admasu et al., 2004). Here, the coldest time of the year is also the driest. Primarily the wet season is associated with the convergence of northeast and southwest airstreams (Bonnefille 1983). Consequently, the biota experience extreme temperature variation within each 24-h period during the whole year, experiencing "summer every day and winter every night" (Hedberg 1964).

2.3 Geology and geomorphology

The Bale Mountains are fragmented due to numerous volcanic plugs, peaks, alpine lakes, and rushing mountain streams that descend into deep rocky gorges on their way to the lowlands. The uppermost part, the Sanetti plateau, is an isolated area covering 211 km^2 at an altitude of about 4,000 m asl bordered by abrupt escarpments to the south. The north and northeast are deeply dissected valleys descending to the northern slope, while to the west lava flows form spectacular bluffs (Osmaston et al.2005). Bale Mountains geology is characterized by a high-altitude volcanic plateau over much older volcanic material formed during the spreading of the EastAfrican Rift Valley system. The petrography is dominated by alkali basalt and tuffs, with occasional rhyolites (Uhlig and Uhlig1991). The mountains were locally glaciated, which shaped their recent geomorphology (Osmaston et al., 2005).

Soils in the area tend to be shallow, gravelly, and recently derived from volcanic rock exposed since glacial retreat (Sillero-Zubiri and Macdonald 1997). Soils consist of a relatively silty loam of reddish-brown to black color (Woldu et al. 1989). Soils located on top of stratigraphically youngest units derive mainly from the Miocene basalt and trachyte lavas that lay over Mesozoic sediments (Umer et al., 2007).

3. Methods

3.1 *Vegetation dynamics, land use, and land cover change*

Geospatial data obtained from Remote Sensing is vital for studying LULC dynamics, identifying biodiversity loss and pattern change hotspots, and identifying significant biodiversity conservation areas. Here, we applied satellite imagery to assess spatiotemporal LULC change in the area over four decades. Systematic analysis of local-scale LULC change studies conducted over a range of timescales helps uncover general principles that explain and predict new land-use changes (Lambin et al., 2003). A better understanding of the degree of influence of each driver of change will contribute to informed decision-making and management of natural ecosystems, mitigate some unnecessary practices, and increase the efficiency of biodiversity conservation and nature's contributions to human wellbeing.

The paper, "Vegetation dynamics, and land use and land cover change in the Bale Mountains, Ethiopia" (Kidane et al., 2012) focus on LULC change as a critical driver of biodiversity change at a local level and its role in shaping trends of biodiversity and its impact on ecosystems' wellbeing. This study identified the main LULC change drivers and their implications for biodiversity patterns change and discussed their importance on spatial arrangements and trajectories of the vascular plants' diversity and distribution along the Bale Mountains.

Remote Sensing data acquired from Landsat Data consist of preprocessed Landsat and SPOT images of four-time steps (1973, 1987, 2000, and 2008). The Landsat Multispectral Scanner (MSS) and Enhanced Thematic Mapper Plus (ETM+) data were acquired from the United States Geological Survey (USGS) *EarthExplorer* homepage (https://earthexplorer.usgs.gov). SPOT images of February 2008 were obtained from SPOT Planet action (http://www.planet-action.org). We chose high-resolution (2.5 m) SPOT data instead of more recent Landsat images for the 2008 time slice due to the known failure of the Scan-Line Protector onboard Landsat 7 on May 21, 2003 (USGS 2009). The images were analyzed using eleven LULC classes predefined based on the dominant plant taxa and cover types of the massif (**Table 1**). Information acquired from such sources provides reliable data that can be traced a few decades back and cover a large swath of land. It facilitates the identification of species diversity hotspots, examining the underlying processes that generate patterns in species diversity, recognizing the threat to plant species diversity, identifying areas of conservation importance and priority, and recommending possible solutions.

Table 1: Vegetation zones and significant habitat types of Bale Mountain. Overlaps in altitude are explained by differences in slope and aspect (based on Miehe and Miehe 1994; Umer et al. 2007).

№	**Cover Classes**	**Aspect**	**Altitude**	**Description**
1	**Afroalpine dwarf shrubs and herbs formation**	**S, SW, and SE**	**3800 - 4385m**	Afroalpine vegetation: including the dwarf shrubs *Helichrysum splendidum*, *Alchemilla haumanii*, the Giant Lobelia (*Lobelia rhynchopetalum*), isolated groves of dwarf *Erica trimera up to 4100m asl.*
2	**Tussock grasslands**	**N and NW**	**3800 - 4050m**	Extensive grasslands: dominated by grasses (*Festuca richardii*) with large number of herbaceous species. Bogs vegetated by *Eriocaulon schimperi* and *Carex monostachya.*
3	**Isolated Erica shrubs**	**S, SW, SE and NW**	**3600 - 4000m**	*Erica* groves within Afroalpine *Helichrysum* heathland. Frequent bush fires keeping Erica in low (up to 3m), shrubby regeneration phases. *Erica trimera* is restricted to distinct patches or solitary individual shrubs.
4	**Ericaceous Belt**	**S, SW and NW**	**3200 - 3600m**	Forest, thickets and scrublands of *Erica trimera* and E. *arborea* communities. *E. trimera* forms tall trees up to 15m height with abundant epiphytes, especially the moss *Antitrichia curtipendula* and the lichen *Usnea articulata*. Above 3,400m a.s.l., which is the well-marked limit of *Hagenia emergents*, *Erica trimera* canopy height diminishes further, and grasses and mosses predominate in the ground layer.
5	**Upper Montane forests**	**N and NW**	**3000 - 3400m**	Dominated by trees such as *Pittosporum viridiflorum, Myrsine melanophloeos, Discopodium eremanthum,* and prominent bushes such as *Rosa abyssinica and Solanum garae*. Dispersed individuals of large trees such as *Hagenia abyssinica, Hypericum revolutum,* and *Juniperus procera*.
6	**Bamboo forest**	**S and SW**	**2800 - 3100m**	Dominated by bamboo *Sinarundinaria alpine* or *Arundinaria alpine*.
7	**Juniperus, Hypericum, and Hygenia Woodland**	**N, and NE**	**2500 - 3400m**	Mainly dominated by a mixed *Juniperus* forest. *Hagenia* and *Hypericum* zone. It is dominated by 12-18m heigh *Hypericum revolutum* and *Rapanea melanophloeos*, accompanied by *Schefflera* and bamboo (*Sinarundinaria alpina*), with *Hagenia abyssinica* up to 25m tall.
8	**Afromontane rainforest**	**S and SW**	**1450 - 3250m**	The rainforest is located mainly at the southern slopes and receives rainfall during more than eight months of a year. It is dominated by *Podocarpus* associated with *Syzygium guineense* and *Aningeria adolfi-friederici*.
9	**Farmland, Settlements, and Fragmented Landscape**	**E, NE, and N**	**2000 - 3400**	Highly fragmented landscape characterized by expanding agricultural land, infrastructure, and settlements.
10	**Barren and burned areas**	**B**		Comprises exposed rocks, bare ground due to land clearing, burning, fallowing, or excessive erosion and sedimentations.
11	**Water bodies**	**W**		The Afroalpine lakes, the rivers, and the hydroelectric dam

Image classification and evaluation were carried out with ENVI-IDL software. The multitemporal image processing chain object-based supervised maximum likelihood classification algorithm is used here. In such an approach, the analyst defines areas where the land cover is known, predefines the LULC types, and the number of classes based on selected parameters. This approach enhances the delineation objectivity, repeatability, and processing efficiency (Duveiller et al., 2008). The land cover class and image classification accuracy assessment cross-checking were done using virtual data sources such as Google Earth photos and high-resolution spot images.

3.2 *Impact of climate change on Ericaceous vegetation*

The role of anthropogenic climate change-induced warming and thermal anomalies is expected to generate novel environmental conditions in the future. The change could favor the expansion and dominance of plants with a more comprehensive habitat range and high phenotypic plasticity, such as ericaceous vegetation. On the Bale Mountains, one-third of the Afroalpine flora are exclusively alpine, while many species have a broader range of distribution that extends to the lower vegetation belts (Kidane et al., 2019). Therefore, we asked whether climate change affects the Afroalpine mountain plants indiscriminately or favors some? Whether the novel environmental conditions or suitable habitats shift favor further expansion and dominance of plants with more comprehensive habitat range and phenotypic plasticity such as Ericaceous vegetation?

In the paper, "The ericaceous vegetation of the Bale Mountains will prevail in the face of climate change' (Kidane et al., 2022 (*in Press*)), we applied Species Distribution Models (SDMs) and model ensembles to study Erica's extent in its current and future range. Recent (SDMs) focus on extinction risks of species or groups rare and under threat of extinction, keystone species, or functional type (Urban 2015). However, information on the potential range retraction of expiation, or fragmentation on widespread species such as Erica, is insufficient. Even slight declines in such Genus can significantly affect ecosystem structure, function, and services (Gaston and Fuller 2008; Warren et al., 2013).

Here, we use four widely applied species modeling algorithms (Generalized Linear Models (GLMs)), Bioclim, Domain, and Support Vector Machines (SVM) algorithms). The current and future bioclimatic predictors variables were downloaded from the WorldClim database (Hijmans et al., 2005). SDMs use individual species and community-based approaches to project potential species distributions in space and time (Hijmans and Elith 2017; Naimi and Araújo 2016). After testing for collinearity, we selected ten historical (current) and future bioclimatic variables. We projected its future distribution under two RCPs (RCP4.5) with average temperature increases of 1.4°C (0.9 to 2.0) and RCP8.5 (the 2070s) with an average temperature increase of 3.7°C (2.6 to 4.8). The dependent (*predicted values*) and independent variables (*bioclimatic predictors and Erica presence values*) were identified, and the models were fitted. Cross-validation was carried out by creating a training and testing data set through random sampling and modeling with known occurrences.

Finally, we ensembled the models by applying model averaging to produce a more reliable prediction. Model ensembles are fitted and evaluated to project potential species distributions in space and time (Naimi and

Araújo 2016). The use of many models and applying model averaging to reduce reliance on a single model is suggested by many as a sound approach for better predictions (e.g., Naimi and Araújo 2016; Hijman and Elith 2017). Hence, the four individual model predictions were ensembled based on their AUC values, and the mean predicted values were calculated. Furthermore, we run a change matrix between the averaged models of the different time steps, i.e., between the current and the 2050s and current and 2070s.

3.3 *Dead end for endemic plant species? A biodiversity hotspot under pressure*

Plant species geographic range shift occurs due to population expansion at the leading edge of their distribution and retraction at the trailing edge (Colwell et al., 2008; Jump et al., 2009). Tropical high mountains are hosting globally significant biodiversity hotspots in small, mostly remote areas. In the paper, "Dead-end for endemic plant species? A biodiversity hotspot under pressure" (Kidane et al., 2019), we studied vascular plant species diversity, distribution, and richness patterns and modeled the potential future impacts of warming due to climate change on those patterns. This study is based on distribution data acquired from nested circular plots along an elevational gradient ranging from 2000m asl to the highest elevation (4385m asl).

The overall richness and the number of Ethiopian (national) and Bale Mountain (local) endemics were calculated for each plot. Generalized Linear Models (GLMs) were used to analyze the relationship between these richness indices and percentages of endemic species with elevation. To allow non-linear relationships, the full models included elevation and elevation^2 as explanatory variables. Stepwise model selection based on the Akaike information criterion (AIC) removed non-relevant variables from the model (R-function *step* in the *stats* package). Poisson error distribution (log-link function) was implemented for all richness-based indices, while binomial error distribution (logit-link function) was used to assess changes in percentage values. The binomial error distribution for percentage values has the advantage of accounting for the number of observations (i.e., species) that underlies a specific percentage value.

Using the same data and literature, we project the future climate impact of three projected regional warming scenarios (+ 2.0ºC, + 3.0ºC, and + 4.0ºC) on the upper and lower distribution range of 448 vascular plant species. In addition, current occurrence records and a lapse rate of 0.6ºC per 100m of elevation were used for the modeling purpose. In general, along mountains, a 1.0ºC increase in mean annual temperature results in a range change of ~167 m in altitude but ~145 km^{-1} in latitude (based on a temperature lapse rate of -6^{0}C km^{-1} altitude and -6.9^{0}C 1000 km latitude) (Sarmiento 1986; Körner 2007; Colwell et al., 2008; Nagy and Grabherr 2009). Out of the total identified 448 vascular plant species, 114 are endemic to Ethiopia, of which 27 are specific to Bale Mountain.

4. Results

4.1 *Vegetation dynamics, land use, and land cover change*

The biodiversity spatial pattern analysis needs to describe, identify, quantify and appraise the landscape structure and composition and detect changes over time and space utilizing various quantitative approaches to geospatial information and analysis tools (Beierkuhnlein 2002b). It is fundamental for conservation priority setting, determining the status and trends of biodiversity, and detecting, monitoring, quantifying and interpreting the implication of LULC change for biodiversity in time and space (Mutke et al. 2001; Beierkuhnlein 2002b). Moreover, it enables the study of landscape patches' spatial relations to quantify the amounts, locations, types, shapes, areas, and directions of landscape patterns (Beierkuhnlein 2002a).

Our result revealed that since the '70s, the area has changed from an entirely natural to a more cultural landscape. The change detection matrices **(Table 2)** revealed that the area has changed from an entirely natural to a cultural landscape over the last fifty years. The natural habitats such as upper montane forest, Afroalpine grasslands, and herbaceous formation increased. Conversely, Afromontane grasslands have decreased in size by more than half (decreased from 1,538 km^2 to 697.6 km^2). Closed *Erica* Forest (the *Ericaceous Belt*) shrunk by 209.64 km^2 and isolated *Erica* shrubs have decreased by 104.27 km^2, Afromontane dwarf shrubs and herbaceous formations have reduced by 184.98 km^2, and Afroalpine dwarf shrubs and herbaceous vegetation lost 290.26 km^2. Despite fluctuations, the Afromontane rainforest (Harenna forest), located south of the Bale Mountains, has remained relatively stable, but the lower margins are recently simplified.

Table 2: The eleven-landscape level LULC classes and their spatial extent with the observed changes over time.

	Code	1973		1987		2000		2008	
Land Use Land Cover classes		**Area (Km^2)**	**percent**	**Area (Km^2)**	**percent**	**Area (Km^2)**	**Percent**	**Area (Km^2)**	**Percent**
Agricultural lands	**Ag**	136.39	1.71	572.19	7.19	1,362.94	17.1	735.39	9.24
Afromatane grassland	**G**	1,538	19.3	1,499.12	18.84	539.81	6.79	697.58	8.77
Afromontane rainforest	**F_r**	2,545	31.98	2,111.8	26.54	2,482.47	31.2	2,527.67	31.77
Uppermontane forest	**F_{um}**	641.19	8.06	720.9	9.06	1,038.93	13.06	1,005.93	12.64
Ericaceous forest	**E_f**	1193.93	15	1,569.06	19.8	747.84	9.4	984.29	12.37
Isolated Erica shrubs	**E_i**	545.62	6.86	502.3	6.3	250.7	3.15	441.35	5.55
Afromontane dwarf Shrubs and herbaceous formations	**S_{dh}**	544.3	6.84	353.4	4.44	577.74	7.26	729.28	9.17
Barren and burned areas	**B**	350.59	4.4	229.16	2.88	648.84	8.15	259.65	3.26
Afroalpine grasslands (Tussock grasslands)	**Tg**	47.89	0.6	66.08	0.83	80.88	1.02	272.25	3.42
Afroalpine dwarf shrubs and herbaceous formations	**Adh**	414.14	5.2	327.75	4.12	211.70	2.66	123.88	1.56
Water bodies	**W**	0.8	0.01	5.98	0.08	15.62	0.2	62.78	0.79
No data		0.00	0.00	0.00	0.00			117.44	1.48
Total		7957.85	100	7957.74	100	7957.47	100	7957.49	100

NB: *The different LULC classes are coded for convenience reasons to easily fit the change detection matrix columns. The code will be used consistently in the following sections.*

The study was conducted without field ground-truthing data collection because the aim was to use and test the significance of proxy information sources (i.e., data gathered from *ex-situ* information sources). Osmaston et al. (2005) underlined that such an approach is logistically efficient, scientifically viable, relatively inexpensive, and time saving. One of the study's focuses was identifying ways of benefiting from using emerging immense geospatial data and geospatial analysis tools in biodiversity conservation, management, and monitoring.

4.2 *Impact of climate change on Ericaceous vegetation*

Species Distribution Models (SDMs) are used for conservation management planning, guide multi-taxon reserve prioritization and selection, and design field surveys (Cayuela et al., 2009; McCune 2016). They are also used to guide the reintroduction of endangered species (Pearson et al., 2006) and detect the status of biodiversity hotspots over a large area (Hallstan 2011; Arenas-Castro et al., 2018). Furthermore, risk assessments of biological or disease invasions, testing ecological theory and comparing historical and recent species distributions (Guisan and Thuiller 2005; Hallstan 2011). Recently, SDMs have been often applied to assess climate change impacts on ecosystems, functional groups, and species (Busby 1986; Guisan and Thuiller 2005). Hence, they are suitable for assessing species and ecosystem status over vast, remote, and inaccessible areas such as the Afroalpine ecosystems (Kreyling et al., 2010).

Our models and model ensembles produced a robust assessment of climate change impacts and projected areas of potential suitable climate space for *Erica* at 1 km resolution and provided the possible future distribution range of *Erica* within the massif **(Figure 2).** The projections for the two future times steps, RCP4.5 (the 2050s) and RCP8.5 (the 2070s) show increase in ericaceous vegetation distribution towards the midaltitude of northwestern, northern parts, eastern, and the Sanetti plateau. The close ericaceous vegetation stands at high altitudes are projected to increase while receding from the lower range of the current distribution across the massif. Towards the second half of the 21st century, ericaceous vegetation will decrease in the upper ranges of the western part of the massif. The results indicate the high likelihood of considerable changes in this biodiversity hotspot in Eastern Africa.

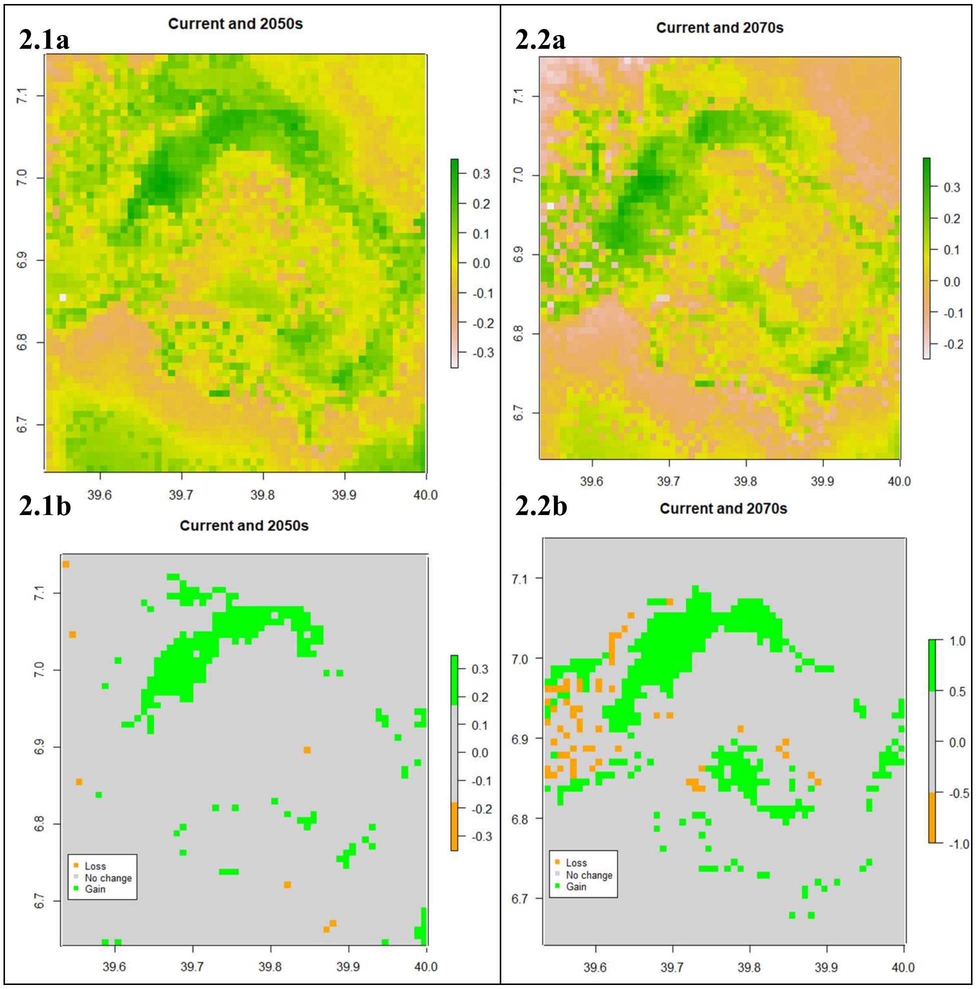

Figure 2. The difference between the averaged models' ensembles of the three-time steps (current and 2050s) (Figure 2.1), and (current and 2070s) (Figure 2.2)). and their respective presence/absence maps (2.1b and 2.2b presence/absence maps; a Gray area represents absolute absence (unsuitable habitat), green area areas of future gain (gained future highly suitable habitats), while orange area habitat loss (current Erica habitat that will lose suitability in the future) during the span of the time step.

Our result indicates the Bale Mountains' ericaceous vegetation will persist as one of the massif's critical ecosystems even under changing climate. The current ericaceous vegetation distribution range is positively correlated to the temperature and precipitation trends, which reaffirms the crucial role of temperature in shaping species distributions along elevational gradients.

4.3 *Dead end for endemic plant species? A biodiversity hotspot under pressure*

Species richness showed a significant mid-elevation richness, and hump-shaped species richness patterns in both aspects (**Figure 3).** It peaks at around 2800 m asl on the wet monsoon exposed southwestern escarpment and at 3500 m asl on the dry north-eastern, highly disturbed, with a shorter gradient (sampling started at around 2800m asl) and eastern transect. After reaching a peak at mid-altitude, overall richness decreases slowly towards the summit. The proportion of endemic species increases monotonically towards the summit on all slopes and peaks at higher elevations for both transects. The percentage of national endemics showed a significant increase with elevation for both transects. However, the percentage of Bale endemics shows an increase for the Northeaster transect, while it peaked at around 3500 m asl for the southwestern transect.

Our species diversity and percent endemic species richness modeling resulted in hump-shaped species richness patterns on both aspects, i.e., the dry north-eastern and the wet monsoon exposed southwestern escarpment. The proportion of endemic species increases monotonically towards the summit on all slopes. We find that future climate change would significantly alter species distribution patterns with a pronounced impact on the unique ecosystems and endemic species restricted to the Afroalpine plateau. Very likely, this will be leading to the extinction of many endemic species.

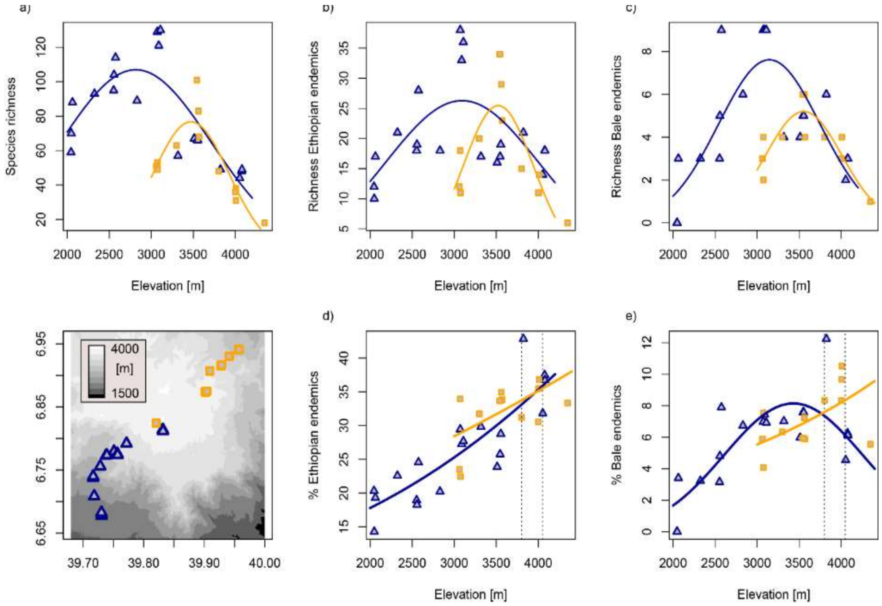

Figure 3: Species diversity and percent endemic species richness along the altitudinal gradient: (a) Overall species richness for both Southwester (blue) and Northeastern (orange) transects. (b) richness of Ethiopian endemics (c) richness of Bale area endemic (d) percent Ethiopian endemics and (e) percent Bale area endemics. The map shows the distribution of sampling plots along an elevational gradient on both transects of the study area. Note that the models depicted in the figures were fitted independently after separating data from the southern and the northern transect. In contrast, the main text reports results of the overall richness model (Table 2 below), exception of the percentage of Bale are endemics (e) where the northern transect shows only a linear fit. The results don't differ qualitatively.

Furthermore, our species lower and upper range limits and projected climate change impact modeling result indicates that future climate change would significantly alter species distribution patterns with a pronounced impact on the unique ecosystems and Afroalpine endemic **(Figure 4)**. The analysis of the upper and lower range of occurrence data of endemics indicated altitudinal range shifts following temperature increase could result in the potential local extinction of 8.7% of all endemic species at a 2.0 °C increase. Some of the threatened plants include *Sedum mooneyi* M.G.Gilbert, *Anthemis tigrensis* J.Gay ex A.Rich., *Helichrysum* *harennensis* Mesfin, *Lobelia rhynchopetalum* (Hochst. ex A. Rich.) Hemsl., *Minuartia filifolia (Forssk.)*, *Senecio schimperi*, *Geranium arabicum* Forssk, *Carex simensis* Hochst. ex A. Rich, *Helichrysum horridum Sch.Bip*, and *Senecio inornatus* DC., three or one in five, are exclusively Bale mountains area endemic. The temperature increase by 3.0°C or 4.0°C predicted a very high rate of endemic extinction, with about 36% (of 41 endemic species) local extinction of endemic species.

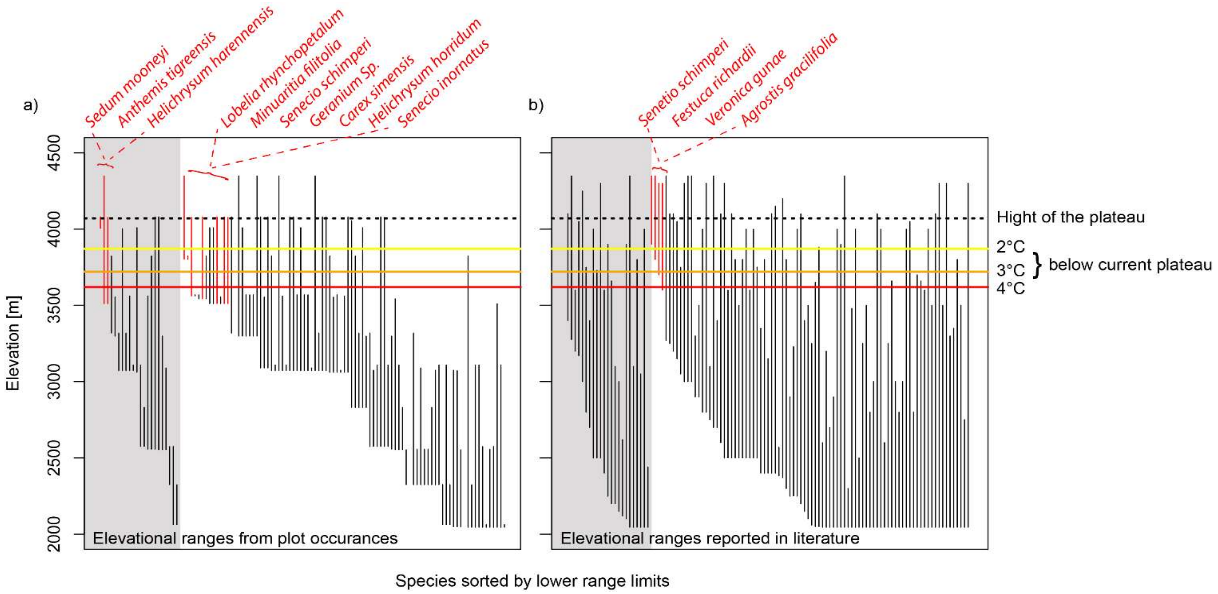

Figure 4: All identified species sorted by lower and upper range limits acquired from plot occurrence data (a) and species documented natural lower and upper range acquired from literature (b). The dashed line indicates the maximum elevation of the plateau, beyond which are three emerging small peaks. Those peaks are small in area and are unlikely to sustain independent populations of species. Hence, here marks the elevation of the plateau as a hard boundary for longterm species survival. The yellow (2.0^{0}C), orange (3.0^{0}C) and red (4.0^{0}C) lines indicate a shift in elevation caused by temperature. Red species ranges loss at least 90% of their current range by the expected temperature increase (4.0^{0}C).

5. Discussion

5.1 The synergistic impacts of climate and LULC change

The Ethiopian mountains have been settled and cultivated for a long time (Getahun 1984; Grepperud 1996; Darbyshire et al., 2003; Hurni et al., 2010). Some recent studies from the Bale Mountains indicate the presence of human pressure (Stephens et al., 2001; Johansson and Granström 2014; Gil-Romera et al., 2019; Ossendorf et al., 2019). Bare hills, small patches of forest, and overgrazed grasslands are characteristic features of the country's geography, especially the highlands (Messerli et al., 1990; Hurni et al., 2010). In many parts of the country, all accessible and productive areas have been transformed and utilized for subsistence farming. However, high altitude-driven unfavorable climate and precipitous slopes related to inaccessibility have been a limiting factor for human exploitation of some parts of these mountains (Hurni et al., 2010). The remaining original vegetation is found confined to the ecosystems that are extreme and inaccessible, "protected areas," and some churches and monasteries (Hurni et al., 2010; Aerts et al., 2016; Orlowska and Klepeis 2018).

Recently, climate change has facilitated LULC change in mountain regions of Africa. Archaeological evidence from other tropical mountains suggests that areas higher than 4,000 m asl have been cultivated in the past during episodes of climatic warming (Barry and Seimon 2000). To date, areas inaccessible due to unfavorable climate are being accessed recently (Hurni et al., 2010). Some recent reports from Northern Ethiopians Mountain suggest that people there are now tilling marginal lands: barley is sown up to 4,100m asl on slopes greater than 45° making the area the highest altitude at which barley is cultivated anywhere in the world (NBSAP 2005; Hurni et al., 2010). Though not particularly investigated, there is observed upward expansion of farmland in the Bale Mountain massif (Kidane et al., 2019). Consequently, these ecosystems are likely to experience significant changes such as conversion to different land-use types, species extinction, and colonization (Hurni et al., 2010; Kidane et al., 2012).

In the Bale massif, biodiversity has been persistently depleted since the 1970s and is currently in imminent danger (Kidane et al., 2012). So far, the main threats to biodiversity conservation in the area are of anthropogenic origin. Increased population accompanied by inadequate economic policies has deepened poverty, widened income inequalities, and forced rural people and others to exploit biodiversity at no longer sustainable rates (Stephens et al., 2001; NBSAP 2005; Chaturvedi et al., 2017). In the Bale massif and across other Ethiopian mountains, individual species, functional groups, entire communities, and ecosystems will be affected because of the synergistic impact of climate and LUCC change. Many (Earn et al., 2000; Sala et al., 2000; Olson et al., 2001; Lambin et al., 2003; Röder et al., 2008; Olson et al., 2008; Hurni et al., 2010) underline the need to combine human-environmental systems across space at multiple scales when assessing the synergistic impacts of drivers of Ecosystems change.

Most recently, the impacts of the socioeconomic transformation due to the intensification of human activities are more immediate and more pronounced in the area. Areas along the major roads are fragmented and are frequented by traffic (vehicles, humans on foot, and horseback). In the past, the wheat and barley farms were at comparatively lower altitudes, while garlic, onion, and other vegetables were at higher altitudes. Recently, crop production expanded up to elevations of 3500m asl, and there is observed intensified livestock grazing (cattle, goats, and bovines) on the plateaus, even around the summits (Kidane et al., 2019).

5.2 Impacts of Land Use Land Cover (LULC) Change

In the past, Ethiopia has failed to protect its natural resources considerably. Jacobs and Schloeder (2001), Stephens et al. (2001), Taddese (2001), Hurni et al. (2010), NBSAP (2005), and Hailu et al. (2018) discuss the failures of past policy, political pressure, and some of the causes of natural resources mishandling and biodiversity loss in Ethiopia. In the Bale Mountains, habitat simplification, conversion, fragmentation, and loss of natural areas over the last sixty years affect the already threatened biodiversity, especially that of the endemic biota (Kidane et al., 2012). Anthropogenic disturbances along the lower elevation of the mountains observed since the early 1980s (Hillman 1986). Other drivers of change such as neglect and lawlessness during political instability and government transition, e.g., (Jacobs and Schloeder 2001), and significant fire incidents of 2000 and 2008 (Wesche et al., 2008; Johansson and Granström 2014) have resulted in severe biodiversity loss.

The study (Kidane et al., 2012) indicated that the massif, including inside Bale Mountain National Park (BMNP), has experienced increasing human pressure for the last sixty years. This is in line with demographic information from the area. In the 1980s, approximately 2500 people lived within the Bale Mountains National Park (BMNP) boundaries (Hillman 1986). The number increased dramatically to about 40,000 in 2007 (FZS 2007). At an annual growth rate of 3%, the park's population is estimated to reach more than 65,000 contemporarily. In addition to the local high birth rate, government villagization and settlement programs, and work-related internal migration contribute to population growth.

The observed accelerated LULC change, and increased biodiversity loss are mainly due to population growth-driven demand for natural resources, predominantly agricultural (mainly land grabbing) and infrastructural expansion, deforestation, and frequent fire. Others such as failed protected area policy, lack of ownership, and citizens' stewardship are also some of the main contributing factors. Yet, climate change is still not investigated and quantified how much of the change is accounted to climate change. Besides, empirical evidence indicated that the fluid natural resource conservation policies, failure of conservation policy, and lack of ownership and citizens' stewardship are the leading causes of LULC change and biodiversity loss.

Habitat loss threatened the Afroalpine range due to high-altitude subsistence agriculture and livestock overgrazing (Amente 2005). Thus, in 2002, the livestock in a discrete area of the Bale Mountains reached an unprecedented density of 314 animals per km^2 (Amsalu and de Graaff 2006). In addition, steep slopes of the high mountains, deforestation, and short-lived showery rain are in the grip of accelerated erosion, and genetic erosion through a mass extinction of endemics. Besides, the recent increase in trekking tourism also contributes to soil erosion and unusual human presence.

One of the most important agelong human activities of the Bale massif is animal husbandry and pastoralism. The frequency and intensity of alpine grazing are increasing because of land degradation and large-scale land grabbing at lower elevations, increased demand for livestock products, and increased frequency of drought in the lowlands. These ecosystems are not adapted to strong herbivore pressure. Now, Afroalpine meadows are increasingly grazed throughout the year by various livestock (mainly cattle, goats, and sheep). It results in soil trampling and the uprooting of many types of grass and herbs, facilitating the local extinction of palatable endemic plant species and eliminating shelter for plant seedlings (Uhlig 1990). In addition, overgrazing has increased the competition between livestock and wildlife (Sillero-Zubiri and Macdonald 1997).

Historically, domestic animal Afroalpine grazing was seasonal and occurred from April to August during the wetter months. Currently, it is happening year-round. Traditionally, local pastoralists drive their herd to the Afroalpine area to use Horas (mineral springs) and graze the delicate Afroalpine vegetation (Hillmann 1990). The Bale pastoralists manage livestock under the godantu system, a vertical transhumance system involving seasonal journeys to the plateau from the surrounding lowlands to graze animals in the Afromontane and Afroalpine vegetation and water from the Afroalpine lakes and access salt from the Afroalpine soils. Afroalpine ecosystems are likely to be irreversibly damaged by overgrazing (taking ecological time scales into account) because the Afroalpine plants exhibit low growth rates and rather long-life cycles (Hillmann 1990; Uhlig 1990; Buytaert et al. 2011). In the face of the synergy of climate and LULC change across the Bale Mountains, the ecosystems will experience permanent alteration and massive biodiversity loss.

5.3 Impacts of climate change

Our studies indicated that the pristine mountain ecosystems are experiencing a change in plant species and functional group composition, diversity, and distribution (Kidane et al., 2019). Climate change will result in habitat quality deterioration and instability which could lead to the loss of species, alteration of species diversity, abundance, and distribution (Malcolm et al., 2006; Lovejoy 2008; Jump et al., 2009; Kreyling et al., 2010). The climate modeling studies (Kidane et al., 2019 and 2022) indicated an upward shift of vascular plants across the massif, hence a change in altitudinal patterns of richness gradients. Even small shifts in the thermal isotherm along altitudinal gradients disrupt the stability of Afroalpine ecosystems affecting the unique plant diversity, distribution, and species richness, leading to unexpected species and functional groups reorganization and massive endemic extinction (Malcolm et al., 2006; Kreyling et al., 2010; Kidane et al., 2019). Besides, the warming-related range shift is likely to result in altitudinal range shifts via dispersal or migration and local loss of populations, which means extinction in the case of spatially restricted endemic species (Walther et al., 2002; Malcolm et al., 2006; Steinbauer et al., 2018).

Furthermore, Peterson et al. (2011) and Gentili et al. (2015) indicated that mountain species would respond to climate change by migrating toward higher elevations and summits, in situ resilience of communities and species within microrefugia, adaptation and evolution through genetic differentiation and/or extinction.

However, the plants and animals of the Bale Mountains Afroalpine ecosystems may not have enough suitable habitat left to escape. Hence, they may face massive range contraction, adaptation, or face the risk of extinction.

In many mountain ecosystems, the topography of the steeper slopes may cause small-scale climatic heterogeneity and range of adjacent thermal niches, allowing species to coexist with differing environmental tolerances in smaller areas (Gentili et al., 2015; Körner and Hiltbrunner, 2021). The mountain species, mainly due to the species limited ability to adapt to new environmental conditions, are challenged by the fast change in ecosystems structure, and function as erosion, flooding, surface structure loss, slope instability, nutrient cycling, and biomass production alters (Beierkuhnlein 2002a). However, species and taxa will respond to climate change independently due to mountains' topographic, climatic, and geological complexity (Sala et al., 2000; Lovejoy and Hannah 2005; Körner and Hiltbrunner, 2021). Species extinction that happens as a singular event affects only the isolated population. Yet, with climate change, when specific biotypes such as Afroalpine ecosystems are affected, the landscape's whole species pool and range of endemics will be affected.

The altitudinal range shift analysis we used (Kidane et al., 2019; 2022) is widely applied to assess the role of climate change on plant diversity and distribution. The methods are powerful for testing biota's ecological and evolutionary responses to geophysical influences, such as temperature changes (Beierkuhnlein 2007; Körner 2007; Nagy and Grabherr 2009). Our analysis of endemics' upper and lower range of occurrence data indicated that at 2.0 °C to 4.0 °C increased 8.7% to 36% of all endemic species.

Our analysis indicates that the plant species diversity around the Bale Afroalpine ecosystem is rich, and the area harbors exceptional concentrations of endemic species. The mountains ecosystem and adjacent tropical mountain rainforests harbor remarkably high numbers of endemic plants and animals. Despite the wide recognition of the area as the world's most significant biodiversity hotspot, the commitment to give the area international recognition, conservation management support, and protection seems to be delayed.

6. Conclusion and Recommendations

Afroalpine mountain ecosystems, particularly those ecosystems at the Afroalpine top, are fragile. These studies documented the biodiversity hotspot's unusual ecosystem-specific challenges due to intensified human activities and projected climate. Land demand for agricultural and infrastructural expansion, deforestation, fire, and intensive livestock grazing are leading causes of biodiversity pattern change and loss. The ecotone between the Afromontane and the Afroalpine area represents a "hotspot of biodiversity loss." Yet recently the Afroalpine vegetation has been getting compromised. How much of the current biodiversity loss is attributed to climate change is not thoroughly studied. However, climate change's impact on Afroalpine mountain biodiversity is expected to be more pervasive.

There is a need to study and maintain the sustainable aspects of the traditional systems. Conservation and adaptation measures are necessary, including expanding the Bale Mountain National Park (BMNP) territory, creating a buffer zone, and limiting human activities and access to the Afroalpine region. Plans that ensure pastoral access and sustainable use of the Afroalpine grasslands and heathlands are needed. Agriculture should be restricted to areas outside the park. Even in areas outside the park, there are patches of seminatural habitat. These areas need to be included in biodiversity conservation strategies.

The pristine mountain ecosystems are experiencing a permanent change in plant species and functional group richness, composition, diversity, and distribution. Our study has proven that the readily available *ex-situ* data sources such as geospatial information from remote sensing (Earth observation databases) and geospatial analysis tools and modeling approaches together with *in-situ* filed data (plot data, ground control points, and field data collection) are effective to assess inaccessible and remote montane ecosystems. It has proven that using such diverse information sources and methods is cost-effective and can produce valid scientific information that contributes to conservation management efforts and identifies protection priority areas in the remote landscape. In addition, it innovatively combines remote sensing data sources, classification using Quantum Geographic Information System (QGIS) (QGIS Development Team 2018) and ground control points, and species distribution models (SDMs).

In the Bale massif, forty yearlong LULC change assessment using *ex-situ* information from Remote Sensing provided a clear synopsis of the last half a century LULC change dynamics of the area. Our finding indicated the observed loss and decline in biodiversity is mainly attributed to human presence: population growth drove high resource needs-driven land demand for agriculture, settlement, and infrastructure. Besides the recent land grabbing, deforestation and fire also result in biodiversity loss and conversion of the natural landscape.

The poor local farmers solely rely on ecosystem services. Hence, they face the most severe and immediate risks of biodiversity loss. Ethiopia's biodiversity has been persistently depleted and is in imminent danger. The past policy failures, top-down decisions, lack of ownership, and citizens' stewardship are some of the leading causes of biodiversity loss. The poor such as subsistence farmers, the rural poor, and traditional societies, have little influence on local to national biodiversity conservation and management planning. Therefore, awareness-raising, all-inclusive bottom-up decision-making, consulting local people and their traditional knowledge, incorporating lessons from sustainable traditional livelihoods, and considering the socio-economic situation of the local inhabitants are important. All-inclusive participatory decision-making practices are critical to maintaining biodiversity and ensuring ecological resilience of Afroalpine mountains ecosystems.

Our findings prove that climate change will endanger a significant part of the unique Afroalpine flora, especially those Bale endemics. Furthermore, intensified human activities are further exacerbating the situation. Conservation management strategies need to address these novel challenges within the massif, with a special focus on the BMNP, including the buffer zone around the boundaries and subzones surrounding the national park. Effective strategies need to acknowledge local people and their socioeconomic situation. Scientific investigation and predictions on the complex interactions between biota (i.e., competition, priority effects, etc.) and climate change are urgently needed for this sky island system. Ecological studies that incorporate social, political, and economic systems and their implications for ecosystems and biodiversity conservation in the face of climate change are needed.

The speed of the ongoing processes clearly shows a need for immediate action if the remaining unique biodiversity of the Bale Mountains is to be salvaged. Conservation and adaptation measures that include the area on the park's periphery within a buffer zone protection plan limit human activities and access to the Afroalpine region. Agriculture needs to be restricted to areas outside the park. Even in areas outside the park, there are patches of seminatural habitat, especially in the areas closer to towns needed to be included in the biodiversity conservation management plan. There is a need for biodiversity management strategies such as monitoring and periodic assessments of ecosystems status.

Overall, the study documented this biodiversity hotspot's rapid and ecosystem-specific change due to intensified human activities and climate change. We believe our findings will contribute to the science and understanding of the potential impacts of climate and LULC change from landscape to species level. The results indicate the high likelihood of considerable changes in this biodiversity hotspot in Eastern Africa.

Therefore, awareness-raising, continuous monitoring, and assessment are essential for the conservation and sustainability of the unique biodiversity. One of the approaches for such an effort can be using state-of-the-art technologies such as remote sensing. The ample geospatial information and advances in analysis tools can support data needs for biodiversity conservation, and monitor change in biotic conditions and disturbances. Geospatial data from remote sensing and analysis tools are becoming familiar among ecologists, geographers, biogeographers, and climatologists—especially those working at larger spatial scales or seeking to understand the broader context.

Main findings and recommendations:

- ✓ The massif is exposed to the synergistic impacts of climate and LULC change, especially the Afroalpine ecosystems and the dwelling unique biodiversity. Therefore, the unique biodiversity and the high level of endemic flora and fauna of Africa's most extensive Afroalpine plateau need immediate intervention for improved conservation management. Recently, the Afroalpine plateau is threatened by climate change-assisted expansion of some prominent cover classes such as Ericaceous vegetation. Therefore, the unique Afroalpine endemic flora and fauna threaten mass extinction.

- ✓ The 1980s expansion of poorly planned mechanized farms, the recent land grabbing, and infrastructural development mid to lower altitudes are pressuring the poor subsistence farmers. Farmland is becoming scarce in the lowland, leaving farmers with little arable land and leaving little room for pastoralists except at higher altitudes.
- ✓ What remains to be learned, especially about the functioning of the Afroalpine ecosystem, will probably be best gathered through long-term monitoring studies carried out by several scientists working together in a multidisciplinary team. Therefore, establishing a long-term alpine research station is needed.
- ✓ Minimize anthropogenic disturbances (deforestation, land clearing for agriculture, infrastructure expansion, etc…) that will hinder the ability of species or ecosystems to withstand climatic events. Avoiding mechanized farming and keeping the sustainable aspects of the traditional land use in the areas closer to the park and the buffer zone are needed.
- ✓ Identify refugia, use areas that are less affected by LULC and climate change, areas as sources for recovery or as destinations of climate-sensitive migrants, and maximize populations of rare and threatened species (Spehn 2011).
- ✓ Despite the wide recognition of the area as the world's most significant biodiversity hotspot, the commitment to give the area international recognition, conservation management support, and protection seems to be delayed. The Bale Mountains need international recognition as a national, continental, and global Afroalpine biodiversity hotspot.
- ✓ The research adopted methodologies that provide insights into the current data sources and tools that effectively assess the status of biodiversity from landscape to plot that can be easily adapted, duplicated, and upgraded by other biogeographers and ecologists.
- ✓ There is a need to encourage state-of-the-art geospatial data and geospatial analysis tools for biodiversity assessment and conservation in remote landscapes. Effective biodiversity conservation, monitoring, and management require accurate, cost-effective, comprehensive, and current information about the status and trends of individual species, ecosystems, and other higher levels of the organization.
- ✓ The is a need to explore the potential impacts of the expansion of commercial coffee farms on the lower peripheries of the moist tropical rainforest, and infrastructure expansion within the buffer zones of the Bale Mountains National Park (BMNP) is still resulting in habitat simplification and biodiversity loss. Most of all, it is endangering the wild cultivars of coffee (*Coffea arabica*).

- ✓ The introduction of exotic plant species such as *Eucalyptus* and *Cupressus* along the main road, villages, and towns is threatening biodiversity. Therefore, there is a need to study the impact of the introduction of alien species in the area.

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References

Admasu, E., Thirgood, S. J., Bekele, A., & Laurenson M. K. (2004). Spatial ecology of the golden jackal in farmland in the Ethiopian Highlands. African Journal of Ecology: doi:10.1111/j.1365-2028.2004.00497.x

Aerts, R., Van Overtveld, K., November, E., Wassie, A., Abiyu, A., Demissew, S., Daye, D.D., Giday K., Haile M., et al. (2016). Conservation of the Ethiopian church forests: threats, opportunities, and implications for their management. Science of the Total Environment: 551-552, 404-414. doi: 10.1016/j.scitotenv.2016.02.034

Amente, G. (2005). Rehabilitation and sustainable use of degraded community forests in the Bale mountains of Ethiopia. Inaugural Dissertation. Faculty of Forest and Environmental Sciences, Albert-Ludwigs-University, Freiburg, Germany.

Amsalu, A., & de Graaff, J. (2006). Farmers views of soil erosion problems and their conservation knowledge at Beressa watershed, central highlands of Ethiopia. Agriculture and Human Values: 23, 99–108 doi:10.1007/s10460-005-5872-4

Arenas-Castro, S., Goncalves, J., Alves, P., Alcaraz-Segura, D., and Honrado, J. P. (2018). Assessing the multi-scale predictive ability of ecosystem functional attributes for species distribution modelling. PLoS One. 18:13(6), 199-292. DOI: 10.1371/journal.pone.0199292

Barry, R.G., and Seimon, A. (2000). Research for mountain area development: Climatic fluctuations in the mountains of the Americas and their significance. Ambio: 29, 364-370.

Beierkuhnlein, C. (2002a). Landscape prognosis: future landscapes. In: Bastian, O., and Steinhardt, U. (eds.): Development and perspectives of landscape ecology. Kluwer, Dordrecht, Boston, London, pp. 195-203.

Beierkuhnlein, C. (2002b). Nature conservation. In: Bastian, O., and Steinhardt, U. (eds.): Development and Perspectives of Landscape Ecology. Kluwer, Dordrecht, Boston, London. pp. 373-385.

Beierkuhnlein, C. (2007). Biogeografie. Die räumliche Organisation des Lebens in einer sich verändernden Welt. Eugen Ulmer Verlag, Stuttgart. 400 pp.

Beierkuhnlein, C., and Jentsch, A. (2005). Ecological importance of species diversity. A review on the ecological implications of species diversity in plant communities in Henry, R. (ed.): Plant Diversity and Evolution: Genotypic and Phenotypic Variation in Higher Plants, CAB International, Wallingford, 249-285.

Bonnefille, R. (1983). Evidence for a cooler and drier climate in the Ethiopian uplands towards 2.5 Mys ago. Nature: doi:10.1038/303487a0

Burgess, N.D., Balmford, A., Cordeiro, N.J., Fjeldsa, J., Kuper, W., Rahbek, C., et al. (2007). Correlations among species distributions, human density, and human infrastructure across the high biodiversity tropical mountains of Africa. Biological Conservation: 134(2), 164-177. doi.org/10.1016/j.biocon. 2006.08.024.

Busby, J.R. (1986). A biogeoclimatic analysis of Nothofagus cunninghamii (Hook.) Oerst. in southeastern Australia. Australian Journal of Ecology: 11, 1–7.

Buytaert, W., Cuesta-camacho, F. & Tobon, C. (2011). Potential impacts of climate change on the environmental services of humid tropical alpine regions. Global Ecology and Biogeography: 20, 19 - 33.

Cayuela, L., Golicher, D. J., Newton, A. C., Kolb, M., de Alburquerque, F. S., Arets, E. J. M. M., Alkemade J. R. M. and Pérez, A. M. (2009). Species distribution modeling in the tropics: problems, potentialities, and the role of biological data for effective species conservation. Tropical Conservation Science: 2(3), 319-352.

Chan, R.Y., Vuille, M., Hardy, D.R., Bradley, R.S. (2008) Intra seasonal precipitation variability on Kilimanjaro and the East African region and its relationship to the large-scale circulation. Theoretical and Applied Climatology: 93, 149-165.

Chaturvedi, R.K., Raghubanshi, A.S., Tomlinson, K.W., and Singh, J.S. (2017). Impacts of human disturbance in tropical dry forests increase with soil moisture stress. Journal of Vegetation Science. 28(5), 997-1007. https://doi.org/10.1111/jvs.12547

Colwell, R.K., Brehm, G., Cardelús, C.L., Gilman, A.C., and Longino, J.T. (2008). Global warming, elevational range shifts, and lowland biotic attrition in the wet tropics. Science: 322, 258–261.

Darbyshire, I., Lamb, H., and Umer, M. (2003). Forest clearance and regrowth in northern Ethiopia during the last 3000 years. The Holocene: 13, 537-546. doi.org/10.1191/0959683603hl644rp

Duveiller, G., Defourny, P., Descle'e, B., & Mayaux, P. (2008). Deforestation in Central Africa: Estimates at regional, national and landscape levels by advanced processing of systematically distributed Landsat extracts. Remote Sensing of Environment: doi:10.1016/j.rse.2007.07.026

Earn, D.J.D., Levin, S.A., and Rohani, P. (2000). Coherence and conservation. Science: 290, 1360 -1364.

Frankfurt Zoological Society (FZS). (2007). Bale Mountains National Park General Management Plan (MBNP-GMP) 2007-2017. Frankfurt. Germany. http://zgf.de. Accessed on December 15, 2009. 238p.

Gaston, K. J. & Fuller, R. A. (2008). Commonness, population depletion and conservation biology. TREE: 23, 14 - 19.

Gehrke, B., Linder, H.P. (2014). Species richness, endemism, and species composition in the tropical Afroalpine flora. Alpine Botany: 124, 165-177. doi 10.1007/s00035-014-0132-0

Gentili, R., Baroni, C., Caccianiga, M., Armiraglio, S., Ghiani, A., and Citterio, S. (2015). Review: Potential warm stage microrefugia for alpine plants: Feedback between geomorphological and biological processes. Ecological Complexity: 21, 87 - 99. doi.org/10.1016/j.ecocom.2014.11.006.

Getahun, A. (1984). Stability and instability of mountain ecosystems in Ethiopia. Mountain Research and Development: 4, 39 - 44. doi.org/10.2307/3673167

Gil-Romera, G., Adolf, C., Benito, B.M., Bittner, L., Johansson, M.U., Grady, D.A., Lamb, H.F., Lemma, B., Fekadu, M., et al. (2019). Long-term fire resilience of the Ericaceous Belt, Bale Mountains, Ethiopia. Biology Letters: 15(7), 1-5. doi:10.1098/rsbl.2019.0357

Grepperud, S. (1996). Population Pressure and Land Degradation: The Case of Ethiopia. Journal of Environmental Economics and Management: 30, 18-33. doi.org/10.1006/jeem.1996.0002

Guisan, A., and Thuiller W. (2005). Predicting species distribution: offering more than simple habitat models. Ecological Letters: 8, 993– 1009. doi:10.1111/j. 1461-0248.2005.00792.x

Hailu, B.T., Fekadu, M., and Nauss, T. (2018). Availability of global and national scale land cover products and their accuracy in mountainous areas of Ethiopia: a review. Journal of Applied Remote Sensing: 12(4), 1-13. doi: 10.1117/1.JRS.12.041502.

Hallstan, S. (2011). Species Distribution Models. Ecological Applications for the Management of Biodiversity. Faculty of Natural Resources and Agricultural Sciences. Department of Aquatic Sciences and Assessment. Uppsala. Sweden.

Hannah, L., Midgley, G.F., Miller, D. (2002). Climate change-integrated conservation strategies. Global Ecology and Biogeography: 11(6), 485-495. doi:10.1046/j.1466-822X.2002.00306.x

Hansen, J., Sato, M., Ruedy, R., Lo, K., Lea, D.W., and Medina-Elizade, M. (2006). Global temperature change. PNAS: 103(39), 4288–14293. doi.org/10.1073/pnas.0606291103

Hedberg, O. (1951). Vegetation belts of the East African mountains. Stockholm: Svenska botaniska fôreningens: 45(1), 140-202.

Hedberg, O. (1964). Features of Afroalpine Plant Ecology. Acta Phytogeographica Suecica: 49, 1-144

Hijmans, R.J., and Elith, J. (2017). Species distribution modeling with R. https://cran.r-project.org/web/packages/dismo/vignettes/sdm.pdf (accessed July 2018).

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., and Jarvis, A. (2005). Very high-resolution interpolated climate surfaces for global land areas. International Journal of Climatology: 25, 1965-1978.

Hillman, J.C. (1986). Conservation in Bale Mountains National Park, Ethiopia. Oryx: 20(2), 89-94. doi:10.1017/S0030605300026314

Hillman, J.C. (1988). The Bale Mountains National Park Area, Southeast Ethiopia and its Management. Mountain Research and Development: 8 (2/3), 253-258.

Hillmann, J. C. (1990). The Bale Mountains National Park area, southeastern Ethiopia, and its management. In B. Messerli & H. Hurni (Eds.), African Mountains and Highlands: Problems and Perspectives (pp. 277-286). Missouri, Walsworth Press: The African Mountain Association (AMA).

Hurni, H., Abate, S., Bantider, A., Debele, B., Ludi, E., Portner, B., Yitaferu, B., and Zeleke, G. (2010). Land Degradation and Sustainable Land Management in the Highlands of Ethiopia. Global Change and Sustainable Development. North-South perspective. Geographica Bernesia: 5, 187-207. doi:10.13140/2.1.3976.5449

Huston, A.M. (1994). Biological Diversity. The Coexistence of Species on Changing Landscapes. Cambridge University press. Athenaeum Press Ltd. Gateshead. 682p.

IPCC (2014). In: Pachauri, R.K., Meyer, L.A. (Eds.), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team. IPCC, Geneva, Switzerland. 151p.

IPCC, (2018). Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)].

Jacobs, M.J., and Schloeder, C.A. (2001). Impacts of conflict on biodiversity and protected areas in Ethiopia Washington, DC: Biodiversity Support Program. 45p.

Jensen, J.R. (2015). Introductory Digital Image Processing: A Remote Sensing perspective. Glenview, IL, Pearson Education Inc.558p.

Johansson, M.U., and Granström, A. (2014). Fuel, fire, and cattle in African highlands: traditional management maintains a mosaic heathland landscape. Journal of Applied Ecology: 51, 1396-1405. doi: 10.1111/1365-2664.12291

Jump, A.S., Matyas, C., and Penuelas, J. (2009). The altitude-for-latitude disparity in the range retractions of woody species. Trends Ecology and Evolution: 24(12), 694-701. doi.org/10.1016/j.tree. 2009.06.007.

Kidane, Y.O. (2022). Synergistic impacts of climate and land use land cover (LULC) change on vascular plants diversity and distribution along the Bale Mountains: *hotpot of Afroalpine biodiversity.* Inaugural Dissertation. Faculty of Biology, Chemistry, and earth Science, Department of Biogeography, University of Bayreuth, Bayreuth, Germany.

Kidane, Y.O., and Beierkuhnlein, C. (2022). Ericaceous vegetation of the Bale Mountains of Ethiopia will prevail in the face of climate change. *Scientific Reports.* 41956e1d-8f45-4470-b788-50835c4372fe | v.3.1 (In press).

Kidane, Y.O., Steinbauer, M.J., and Beierkuhnlein, C. (2019). Dead end for endemic plant species? A biodiversity hotspot under pressure. Global Ecology and Conservation, 19, 1-12. doi.org/10.1016/j.gecco. 2019.e00670

Kidane, Y.O.., Stahlman, R., Beierkuhnlein, C. (2012). Vegetation dynamics, and land use and land cover change in the Bale Mountains, Ethiopia. Environmental Monitoring Assessment: 184 (12), 7473-7489. doi.org/10.1007/s10661-011-2514-8.

Körner, C. (2007). The use of 'altitude' for ecological research. Trends in Ecology and Evolution: 22 (11), 569-574. doi.org/10.1016/j.tree.2007.09.006.

Körner, C.; Hiltbrunner, E. (2021). Why Is the Alpine Flora Comparatively Robust against Climatic Warming? Diversity: 13, 383. https://doi.org/10.3390/ d13080383

Kreyling, J., Wana, D., Beierkuhnlein, C. (2010). Climate warming and tropical plant species – consequence of potential upslope shift of isotherms in southern Ethiopia. Diversity and Distribution: 16, 593 - 605. doi.org/10.1111/j.1472-4642.2010.00675.x.

Lambin, E.F., Lambin, E.F., Geist, H.J, and Lepers, E. (2003). Dynamics of land-use and landcover change in tropical regions. Annual Review of Environment and Resources: 28, 205–241. doi.org/10.1146/annurev. energy. 28.050302.105459

Laurenson, K., Sillero-Zubiri, C., Thompson, H., Shiferaw, F., Thirgood, S., & Malcolm, J. (1998). Disease as a threat to endangered species: Ethiopian wolves, domestic dogs and canine pathogens. Animal Conservation: doi:10.1111/j.1469-1795.1998.tb00038.x

Lovejoy, T. (2008). Climate change and biodiversity. Revue scientifique et technique (International Office of Epizootics): 27 (2), 331-338.

Lovejoy, T.E. and Hannah, L. (2005). Climate Change and Biodiversity. Yale University Press. New Haven. USA.

Malcolm, J.R., Liu, C., Neilson, R.O., Hansen, A., Hannah, L. (2006) Global warming and extinctions of endemic species from biodiversity hotspots. Conservation Biology: 20(2), 538 - 548. doi.org/ 10.1111/j.1523-1739.2006.00364.x.

McCune, J.L. (2016). Species distribution models predict rare species occurrences despite significant effects of landscape context. Journal of Applied Ecology: 53. 1871–1879. doi: 10.1111/1365-2664.12702

Messerli, B., and Ives, J.D. (1997). Mountains of the world: a global priority. edited by B. Messerli and J.D. Ives. Parthenon Pub. Group, New York. 495p.

Messerli, B., Hurni, H., Woldesemait, B., Tedla, S., Ives, J.D., and Woldemariam, M. (1990). African mountains and Highlands: An introduction. In Messerli, B., and Hurni, H. (eds.). African Mountains and Highlands: Problems and Perspectives. The African Mountain Association (AMA). Walsworth Press Co., Inc., Missouri.

Miehe, G., and Miehe, S. (1994). Ericaceous Forests and Heathlands in the Bale Mountains of South Ethiopia: Ecology and Man's Impact. Stiftung Waldurhaulting in Afrika. Humburg,Germany. 206 p.

Millennium Ecosystem Assessment (MEA), (2005). Status and trends in mountain systems. Washington: World Resources Institute.

Monasterio, M., and Vuilleumier, F. (1986). Introduction: High tropical Mountain Biota of the World. In High Mountains Tropical Biogeography. Eds. Vuilleumier, F. and Monasterio, M. Published by Oxford University Press and the American Museum of Natural History. Oxford University Press. New York. USA.

Mutke, J., Kier, G., Braun, G., Schultz, Chr, Barthlott, W. (2001). Patterns of African vascular plant diversity: a GIS based analysis. Systematics and Geography of Plants: 71, 1125-1136. doi: 10.2307/3668744

Nagy, L., and Grabherr, G. (2009) The Biology of Alpine Habitats. Oxford University Press, Oxford. 376p.

Naimi, B., and Araújo, M.B. (2016). SDM: a reproducible and extensible R platform for species distribution modeling. Ecography: 39, 368–375. DOI: 10.1111/ecog.01881.

National Biodiversity Strategy and Action Plan (NBSAP) (2005). Democratic Republic of Ethiopia. Institute of Biodiversity Conservation. Addis Ababa. Ethiopia. http://www.cbd.int/doc/world/et/et-nbsap-01-en.pdf. Accessed on September 20, 2009.

Niang I, Ruppel OC, Abdrabo MA, Essel A, Lennard C, Padgham J, Urquhart P. 2014. Africa. In: Barros VR, Field CB, Dokken DJ, Mastrandrea MD, Mach KJ, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL, editors. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom, and New York, NY: Cambridge University Press, pp 1199–1265.

Nogués-Bravo, D., López-Moreno, J.I., and Vicente-Serrano, S. M. (2012). Climate Change and its Impact. Mediterranean Mountain Environments. Mediterranean Mountain Environments: 185-201. doi: 10.1002/9781119941156.ch9

Nsengiyumva, P. (2021). African Mountains in a Changing Climate: Trends, Impacts, and Adaptation Solutions. Mountain Research and Development: 39(2), 1-8. https://doi.org/10.1659/MRD-JOURNAL-D-19-00062.1

Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., et al., (2001). Terrestrial Ecoregions of the World: A New Map of Life on Earth. BioScience: 51(11), 933 - 938. doi.org/10.1641/0006-3568(2001)051[0933:TEOTWA]2.0.CO;2

Olson, J. M., Alagarswamy, G., Andresen, J. A., Campbell, D. J., Davis, A. Y., et al. (2008). Integrating diverse methods to understand climate–land interactions in East Africa. Geoforum: 39(2), doi:10.1016/j.geoforum. 2007.03.011.

Orlowska, I., and Klepeis. P. (2018). Ethiopian church forests: a socio-religious conservation model under change. Journal of Eastern African Studies: 12(4): 674-695. doi:10.1080/17531055.2018.1519659

Osmaston, H.A., Mitchell, W.A., Osmaston, J.A.N. (2005). Quaternary glaciation of the Bale mountains, Ethiopia. Journal of Quaternary Science: 20(6), 593 – 606. doi:10.1002/jqs.931

Ossendorf, G., Groos, A.R., Bromm, T., Tekelemariam, M.G., Glaser, B., Lesur, J., et al. (2019). Middle Stone Age foragers resided in high elevations of the glaciated Bale Mountains, Ethiopia. Science: 365(6453), 583–587. doi: 10.1126/science.aaw8942.

Pearson, R. G. 2006. Species' Distribution Modelling for Conservation Educators and Practitioners. Lessons in Conservation: 3. 54-89

Peters, G. P. et al. (2012). Rapid growth in CO2 emissions after the 2008_2009 global financial crisis. Nature Climate Change: 2, 2-4.

Peterson, A.T., Soberón, J., Pearson, R.G., Anderson, R.P., Martinez-Meyer, E., Nakamura, M., and Araújo, M.B. (2011). Ecological Niches and Geographic Distributions. Monographs in Population Biology -49. Princeton University Press, Princeton, and Oxford. 314 pp.

Pihl, E., Martin, M.A., Blome, T., Hebden, S., Jarzebski, M.P., Lambino, R.A., et al. (2019). 10 New Insights in Climate Science. Future Earth & The Earth League, Stockholm. 34p.

QGIS Development Team (2018). QGIS Geographic Information System. Open-Source Geospatial Foundation Project. http://qgis.osgeo.org.

R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing [Internet]. http://www.R-project.org/.

Rahbek, C., Borregaard, M.K., Antonelli, A., Colwell, R.K., Holt, B.G., Nogues-Bravo, D., et al. (2019) Building Mountain biodiversity: Geological and evolutionary processes. Science: 365 (6458), 1114-1119. doi: 10.1126/science.aax0151.

Razgour, O., Kasso, M., Santos, H., and Juste, J. (2020). Up in the air: Threats to Afromontane biodiversity from climate change and habitat loss revealed by genetic monitoring of the Ethiopian Highlands bat. Evolutionary Application: 2021 (14), 794-806. doi.org/10.1111/eva.13161.

Röder, A., Stellmes, M., Hill, J., Kuemmerle, T., and Tsiourlis, G.M. (2008). Analyzing land cover change using time series analysis of Landsat data and geoinformation processing. A natural experiment in Northern Greece. Proceedings of SPIE - The International Society for Optical Engineering: 7104, 1-11. doi: 10.1117/12.800265

Sala, O.E., Chapin, F.S., Armesto, J.J., Berlow. E., Bloompeld, J., Dirzo, R., et al. (2000). Global biodiversity scenarios for the year 2100. Science: 287 (5459), 1770 – 1774. doi:10.1126/science.287. 5459.1770

Sarmiento, G. (1986). Ecological Feature of Climate in High Tropical Mountains. In High Mountains Tropical Biogeography. Eds. Vuilleumier, F. and Monasterio, M. Published by Oxford University Press and the American Museum of Natural History. Oxford University Press. New York. USA 649p.

Sillero-Zubiri, C., & Macdonald, D. W. (1997). The Ethiopian Wolf: Status Survey and Conservation Action plan. IUCN Canid Specialist Group, Gland, Switzerland and Cambridge, UK.

Spehn, E. (2011). Mountain Biodiversity: Effects of climate change and how to manage them. Plant ecology and diversity: 60, 40-43. doi:10.1080/17550874.2012.698660

Steinbauer, M.J., Grytnes, J.A., Jurasinski, G., Kulonen, A., Lenoir, J., Pauli, H., et al. (2018). Accelerated increase in plant species richness on mountain summits is linked to warming. Nature: 556(7700), 231-234. doi.org/10.1038/s41586-018-0005-6.

Stephens, P. A., d'Sa, C. A., Sillero-Zubiri, C., & Leader-Williams, N. (2001). Impact of livestock and settlement on the large mammalian wildlife of Bale Mountains National Park, Southern Ethiopia. Biological Conservation: 100, 307–322. doi:10.1016/S0006-3207(01)00035-0.

Taddese, G. (2001). Land Degradation: A challenge to Ethiopia. Environmental Management: 27, 815-824.

Uhlig, S. K. (1990). Mountain forests and the upper tree limit on the Southeastern plateau of Ethiopia. In B. Messerli & H. Hurni (Eds.), African Mountains and Highlands: Problems and Perspectives (pp. 237-248). Missouri, Walsworth Press: The African Mountain Association (AMA).

Uhlig, S. K., & Uhlig, K. (1991). Mountain chronicles. Studies on the altitudinal zonation of forests and alpine plants in the central Bale Mountains, Ethiopia. Mountain Research and Development: 11(2), 153-256.

Umer, M., Lamb, H.F., Bonnefille, R., Lezine, A.M., Tiercelin, J.J., Gibert, E., Cazet, J.P., Watrin, J. (2007). Late Pleistocene and Holocene vegetation history of the Bale mountains, Ethiopia. Quaternary Science Reviews: 26 (17-18), 2229-2246. doi.org/10.1016/j.quascirev.2007.05.004

Urban, M.C. (2015). Accelerating extinction risk from climate change. Science: 348, 571–573. doi: 10.1126/science. aaa4984

Walther, G.R., Post, E., Convey, P., Menzel, A., Parmesank, C., Beebee, T.J.C., Fromentin, J.M., Hoegh Guldberg, O., Bairlein, F. (2002). Ecological responses to recent climate change. Nature: 416, 389-395. doi.org/10.1038/416389a.

Warren, R., VanDerWal, J., Price, J., Welbergen, J.A., Atkinson, I., Ramirez-Villegas, J., Osborn, T.J., Jarvis, A., Shoo, L.P., Williams, S.E., and Lowe, J. (2013). Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. Nature Climate Change: 3:678-682. DOI: 10.1038/NCLIMATE1887

Wesche, K. (2003). The importance of occasional droughts for Afroalpine landscape ecology. Journal of Tropical Ecology, 19(2), 197-208. doi.org/10.1017/S0266467403003225

Wesche, K., Cierjacks, A., Assefa, Y., Wagner, S., Fetene, M., and Hensen, I. (2008). Recruitment of trees at tropical alpine treelines: Erica in Africa versus Polylepis in South America. Plant Ecology and Diversity: 1(1), 35–46. doi.org/10.1080/17550870802262166

Wesche, K., Miehe, G., and Kaeppeli, M. (2000). The significance of fire for Afroalpine Ericaceous vegetation. Mountain Research and Development: 20, 340-347. doi.org/10.1659/0276-4741(2000)020[0340:TSOFFA] 2.0.CO;2

Woldu, Z., Feoli, E., & Nigatu, L. (1989). Partitioning an elevation gradient of vegetation from south-eastern Ethiopia by probabilistic methods. Vegetatio: doi:10.1007/BF00045524

Appendix I: The Bale mountains species list with growth form, red list status, distribution and endemism, and upper and lower distribution range. On the Distribution and endemism statues: EE- Ethiopian Endemic, EA common all over East Africa and some part of the world, and BE exclusively Bale Mountains Endemics.

No	*Species*	Family	Growth Form	Red List	Distribution and Endemism	Lower Range	Upper Range
1	*Acanthopale aethopica* Enserum (ined.)	Acanthaceae	shrub		EE	1600	2600
2	*Acanthopale pubescens* (Engl.) C.B. Cl.	Acanthaceae	Shrub		EA	2300	2750
3	*Acanthus sennii* Chiov.	Acanthaceae	Shrub	Yes	EE	1700	3200
4	*Achyranthes aspera* L.	Amaranthaceae	Herb		EA	750	3050
5	*Achyrocline stenoptera* (DC.) Hilliard & Burtt	Asteraceae (Compositae)	Herb		EA	1800	3500
6	*Adhatoda schimperi* Hochst. Ex Nees	Acanthaceae	Herb		EE	1300	2700
7	*Agrocharis incognita* Heyw. & Jury.	Apiaceae (Umbelliferae)	Herb		EA	1750	2900
8	*Agrocharis melanantha* Hochst. H sem	Apiaceae (Umbelliferae)	Herb		EA	1000	4200
9	*Agrostis gracilifolia* C. E. Hubbard	Poaceae (Gramineae)	Gram		EA	3600	4300
10	*Agrostis quinqueseta* (Hochst ex. Steud.) Hochst	Poaceae (Gramineae)	Gram		EA	2500	4300
11	*Agrostis volkensii* Stapf	Poaceae (Gramineae)	Gram		EA	3000	3900
12	*Aira caryophyllea* L.	Poaceae (Gramineae)	Gram		EA	2400	4500
13	*Ajuga remota* Benth.	Lamiaceae (Labiatae)	Herb		EA	1500	3400
14	*Alchemilla abyssinica* Fresen	Rosaceae	Herb		EA	2500	4400
15	*Alchemilla cryptantha* A. Rich.	Rosaceae	Herb		EA	1300	4050
16	*Alchemilla fischeri* Engl.	Rosaceae	Herb		EA	2100	3440
17	*Alchemilla haumannii* Rothm	Rosaceae	Shrub	Yes	EE	3000	4250
18	*Alchemilla microbetula* Th. C. E. Fr.	Rosaceae	Herb		EA	3200	4400
19	*Alchemilla pedata* Hochst. ex A. Rich.	Rosaceae	Herb		EA	1800	4000
20	*Alepidea penduncularis* A.Rich. (A. longifolia E. Mey.)	Apiaceae (Umbelliferae)	Herb		EA	1000	3800
21	*Alisma plantagoaquatica* L.	Alismataceae	Herb		EA	950	2300
22	*Allophylus macrobotrys* Gilg.	Sapindaceae	Shrub/tree		EA	1400	2500
23	*Amorphophallus abyssinicus* (A. Rich.) N.E.Br.	Araceae	Herb		EA	2700	4500
24	*Anagallis serpens* Hochst. ex. DC.	Primulaceae	Herb		EA	2500	3600
25	*Andropogon lima* (Hack.) Stapf	Poaceae (Gramineae)	Gram		EA	3000	3700
26	*Andropogon pratensis* Hochst ex back	Poaceae (Gramineae)	Gram		EA	2000	4100
27	*Anemone thomsonii* Oliv.	Ranunculaceae	Herb		EA	2700	3500
28	*Aningeria adolfi-friederici* Engl. Robyns & Gilbert	Sapotaceae	Tree		EA	1350	2450
29	*Anogramma leptophylla* (L.) Link	Hemionitidaceae (Aspleniacea)	Herb		EA	1770	3900

No	*Species*	Family	Growth Form	Red List	Distribution and Endemism	Lower Range	Upper Range
30	*Anthemis tigreensis* J. Gay ex A. Rich.	Asteraceae (Compositae)	Herb		EA	1800	4620
31	*Anthospermum herbaceum* L.f.	Rubiaceae	Herb		EA	2000	3000
32	*Anthoxanthum aethiopicum* I. Hedberg	Poaceae (Gramineae)	Gram		EE	2700	4500
33	*Anthriscus sylvestris* (L.) Hoffm.	Apiaceae (Umbelliferae)	Herb		EA	1530	3600
34	*Arabis alpina* L.	Brassicaceae (Cruciferae)	Herb		EA	2000	4350
35	*Arabis thaliana L.*	Brassicaceae (Cruciferae)	Herb		EA	1450	4400
36	*Ardisiandra wettsteinii* R. Wagner	Primulaceae	Herb		EA	2850	3500
37	*Argyrolobium ramosissimum* Bak.	Fabaceae (Leguminosae)	Herb		EA	2000	3550
38	*Argyrolobium rupestre* (E. Mey.)	Fabaceae (Leguminosae)	Shrub		EA	2000	2700
39	*Artemisia afra* Willd.	Compositae	Herb		EA	1500	4050
40	*Artemisia schimperi* Sch. Bip.ex Engl.	Asteraceae (Compositae)	Herb		EE	3200	4100
41	*Arthropteris monocarpa* (Cordem.) C. Chr.	Oleandraceae (Aspleniacea)	Epiphyte		EA	1000	2700
42	*Arundinaria alpina* K. Schum.	Poaceae (Gramineae)	Gram		EA	2200	4000
43	*Asparagus africanus* Lam.	Poaceae (Gramineae)	Shrub		EA	0	3800
44	*Aspelenium theciferum* (HBK) Mett.	Aspleniaceae (Filices)	Shrub		EA	2000	4350
45	*Asplenium abyssinicum* Fee.	Aspleniaceae (Filices)	Epiphyte		EA	1700	3250
46	*Asplenium adiantum-nigrum* L.	Aspleniaceae (Filices)	Herb		EA	2600	3900
47	*Asplenium aethiopicum* (Burm. F.) Becherer	Aspleniaceae (Filices)	Epiphyte		EA	2100	3600
48	*Asplenium anisophyllum* O. Kuntze	Aspleniaceae (Filices)	Epiphyte		EA	2250	2800
49	*Asplenium friesiorum* C. Chr.	Aspleniaceae	Fern		EA	2370	3060
50	*Asplenium monanthes* L.	Aspleniaceae (Filices)	Epiphyte		EA	2370	3060
51	*Asplenium protensum* Schrader.	Aspleniaceae (Filices)	Epiphyte		EA	1600	3000
52	*Asplenium sandersonii* Hook.	Aspleniaceae (Filices)	Epiphyte		EA	1580	2500
53	*Asplenium sp. aff. actinopteroides* A. Peter	Aspleniaceae (Filices)	Herb		EA	2500	4250
54	*Asplenium sp. aff. demerkense* Hieron.	Aspleniaceae (Filices)	Herb		EE	2900	3300
55	*Barbarea intermedia* Boreau	Brassicaceae (Cruciferae)	Herb		EA	3000	4200
56	*Bartsia decurva* Hochst.ex Benth.	Scrophulariaceae	Shrub		EA	2500	4100
57	*Bartsia longiflora* Hochst.ex Beth.	Scrophulariaceae	Shrub		EA	2400	4000
58	*Bartsia petitiana* (A.Rich) Hemsl.	Scrophulariaceae	Herb		EA	2480	2520
59	*Bartsia trixago* L.	Scrophulariaceae	Herb		EA	2100	3500
60	*Basella alba L.*	Basellaceae	Herb		EA	1600	2370
61	*Bersama abyssinica* Fresen.	Melianthaceae	Tree/shrub		EA	1700	2715
62	*Bidens camporum* (Hutch.) Mesfin.	Asteraceae (Compositae)	Herb		EA	1000	3050

No	*Species*	Family	Growth Form	Red List	Distribution and Endemism	Lower Range	Upper Range
63	*Bidens macroptera* (Sch. Bip. ex Chiov.) Mesfin	Asteraceae (Compositae)	Herb			2400	3300
64	*Bidens rueppellii* (Sch.Bip. ex Sch.Bip.) Sherff	Asteraceae (Compositae)	Herb/shrub		EA	2400	3300
65	*Blaeria spicata* Hochst. ex. A. Rich.	Ericaceae	Herb		EA	2300	4000
66	*Bromus cognatus* Steud	Poaceae (Gramineae)	Gram		EE	1800	2300
67	*Brucea antidysenterica* J.F. Mill.	Simaroubaceae	Shrub/ tree		EA	1650	2800
68	*Buddleia polystachya* Fresen	Scrophulariaceae	Shrub		EA	1000	2700
69	*Calpurnia aurea* (Ait.) Benth.	Fabaceae (Leguminosae)	Shrub/ tree		EA	1650	2550
70	*Campanula edulis* Forsk.	Campanulaceae	Herb		EA	1000	3800
71	*Canthium oligocarpum* Hiern	Rubiaceae	Shrub/ tree		EA	1350	3000
72	*Cardamine hirsuta* L.	Brassicaceae (Cruciferae)	Herb		EA	2200	3800
73	*Cardamine obliqua* A. Rich	Brassicaceae (Cruciferae)	Herb		EA	1980	4100
74	*Carduus camaecephalus* Desf.	Asteraceae (Compositae)	Herb		EA	2890	3100
75	*Carduus nyassanus* (S. Moore) R.E. Fries.	Asteraceae (Compositae)	Herb		EA	2890	3100
76	*Carduus schimperi* Sch. Bip.	Asteraceae (Compositae)	Shrub		EA	3000	4300
77	*Carex bequaertii* De Wild.	Cyperaceae	Herb		EA	2500	3800
78	*Carex coniferta* Hochst. ex A. rich.	Cyperaceae	Herb		EA	2200	3600
79	*Carex johnstonii* Böck.	Cyperaceae	Herb		EA	2000	3280
80	*Carex monostachya* A. Rich.	Cyperaceae	Herb		EA	2750	3990
81	*Carex peregrina* Link.	Cyperaceae	Herb		EA	2930	3440
82	*Carex petitiana* A. Rich.	Cyperaceae	Herb		EA	2150	3100
83	*Carex simensis* A. Rich.	Cyperaceae	Herb		EA	2600	4100
84	*Carex steudneri* Böck.	Cyperaceae	Herb		EA	2000	3800
85	*Carissa spinarum* L.	Apocynaceae	Shrub		EA	550	2500
86	*Cassipourea malosana* (Baker) Alston	Rhizophoraceae	Tree/shrub		EA	1250	3100
87	*Celsia scrophulariaefolia* Hochst.	Scrophulariaceae	Herb		EE	2500	3500
88	*Celtis africana Burm.* F.	Ulmaceae	Tree		EA	1300	2500
89	*Centella asiatica* (L.) Urban	Apiaceae (Umbelliferae)	Herb		EA	0	3480
90	*Cerastium afromontanum* T.C.E. Fries & Weimarck.	Caryophyllaceae	Herb		EA	2500	4000
91	*Cerastium indicum* Wight & Arn.	Caryophyllaceae	Herb		EA	2600	3500
92	*Cerastium octandrum* A. Rich.	Caryophyllaceae	Herb		EA	2450	3900
93	*Cheilanthes farinosa* (Forssk.) Kaulf.	Adianthaceae	Fern		EA	2400	3600
94	*Chiliocephalum tegetum* Mesfin.	Asteraceae (Compositae)	Herb		EE	2400	3600
95	*Chlorophytum tetraphylum* (L. f.) Baker	Anthericaceae	Herb		EA	1250	3400

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96	*Cineraria abyssinica* Shultz-Bip. ex A. Rich.	Asteraceae (Compositae)	Herb		EE	2100	3900
97	*Cineraria deltoidea* Sond.	Asteraceae (Compositae)	Herb		EA	2800	4150
98	*Cineraria sebaldii* Cufod.	Asteraceae (Compositae)	Herb		EE	2370	4200
99	*Cirsium dender* Friis	Asteraceae (Compositae)	Herb		EE	600	2400
100	*Cissus Petiolata* Hook.f.	Vitaceae	Climbers		EA	600	2400
101	*Clematis hirsuta* Perr. & Guill.	Ranunculaceae	Climber		EA	850	3200
102	*Clematis simensis* Fresen.	Ranunculaceae	Climbers		EA	1500	3350
103	*Clerodendron myricoides* (Hochst.) Vatke.	Lamiaceae (Labiatae)	Shrub		EA	700	2600
104	*Clutia abyssinica* Jaub. & Spach.	Euphorbiaceae	Herb/shrub		EA	1450	2950
105	*Clutia lanceolata* Frossk.	Euphorbiaceae	Herb/shrub		EA	1270	3250
106	*Colutea abyssinica* Kunth. & Bouche	Fabaceae (Leguminosae)	Shrub		EA	1600	4000
107	*Combretum molle* R. Br. ex G. Don	Combretaceae	Tree		EA	500	2500
108	*Commelina africana* L.	Commelinaceae	Herb		EA	900	3300
109	*Conium maculatum* L.	Apiaceae (Umbelliferae)	Herb		EA	2400	3350
110	*Conyza bonariensis* (L.) Cronq.	Asteraceae (Compositae)	Herb		EA	1290	2600
111	*Conyza hochstetteri* Sch.Bip.ex A.Rich.	Asteraceae (Compositae)	Herb		EA	1300	3050
112	*Conyza nana* Sch. Bip. ex Oliv & Hiern	Asteraceae (Compositae)	Herb		EE	2900	3500
113	*Conyza schimperi* Sch. Bip. Ex A. Rich.	Asteraceae (Compositae)	Herb		EA	1500	3300
114	*Conyza spinosa* Sch. Bip. Ex. Oliv. & Hiern	Asteraceae (Compositae)	Shrub		EE	2500	3800
115	*Conyza steudelii* Sch. Bip. Ex. A.Rich.	Asteraceae (Compositae)	He		EA	2200	3000
116	*Conyza tigrensis* Oliv. & Hiern	Asteraceae (Compositae)	Herb		EA	1650	2550
117	*Conyza vernonioides* Schultz-Bip ex A.Rich	Asteraceae (Compositae)	Herb/shrub		EA	3000	3600
118	*Cordia africana* Lam.	Boraginacea (Begoniaceae)	Tree		EA	700	2550
119	*Corydalis mildbraedii* Fedde.	Fumariaceae	Herb		EA	3040	3280
120	*Cotula abyssinica* Schultz-Bip. ex A. Rich.	Asteraceae (Compositae)	Herb		EA	2950	3220
121	*Cotula cryptocephala* Schultz-Bip. ex A. Ric	Asteraceae (Compositae)	Herb		EA	2890	3800
122	*Crassocephalum macropappum* (Sch. Bip. ex A. Rich.) S. Moore	Asteraceae (Compositae)	Herb		EE	2383	2570
123	*Crassula alsinodes* (Hook.F.) Engl.	Crassulaceae	Herb		EA	2200	3440
124	*Crassula granvikii* Mildbr.	Crassulaceae	Herb		EA	1650	3900
125	*Crassula schimperi* Fisch. & Mey.	Crassulaceae	Herb/shrub		EA	1500	4200
126	*Craterostigma pumilum* Hochst.	Scrophulariaceae	Herb		EA	1900	2650
127	*Crepis carbonaria* Schultz-Bip.	Asteraceae (Compositae)	Herb		EA	2400	3400

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128	*Crepis rueppellii* Schultz-Bip.	Asteraceae (Compositae)	Herb		EA	1100	4300
129	*Crepis tenerrima* (Sch. Bip. ex A. Rich.) R.E. Fries	Asteraceae (Compositae)	Herb		EE	2750	3100
130	*Crinum abyssinicum* Hochst. ex A.Rich.	Amaryllidaceae	Herb		EA	1650	3300
131	*Crotalaria incana* L. subsp. purpurascens (Lam.)	Fabaceae	Herb		EA	1200	2700
132	*Croton macrostachyus* Hochst.ex Del.	Euphorbiaceae	Shrub/ tree		EA	500	2350
133	*Cucumis ficifolius* A. Rich.	Cucurbitaceae	Herb		EA	1300	2700
134	*Curcurligo pilosa* (Schum. & Thonn.) Engl.	Hypoxidaceae	Herb		EA	550	3000
137	*Cussonia holstii* Harms ex Engl.	Araliaceae	Tree		EA	1100	2600
138	*Cyathula cylindrica* Moq.	Amaranthaceae	Herb		EA	900	3100
139	*Cyathula polycephala* Bak.	Amaranthaceae	He		EA	1750	3000
140	*Cyathula uncinulata* (Schrad.) Schinz.	Amaranthaceae	Herb		EA	1000	3000
141	Cyclospermum leptophyllum (Pers.) Sprague	Apiaceae	Herb		EA	1000	3000
142	*Cyniopsis obtusifolia* Skan.	Scrophulariaceae	Herb		EA	1000	3000
143	*Cynoglossum alpinum* (Brand) Riedl.	Boraginaceae (Begoniaceae)	He		EA	2000	3250
144	*Cynoglossum amplifolium* Hochst. ex A. DC.	Boraginaceae (Begoniaceae)	Herb		EA	1500	3500
145	*Cynoglossum coeruleum* DC.	Boraginaceae (Begoniaceae)	Herb		Endemic	2700	3400
146	*Cynoglossum globlatum*	Boraginaceae (Begoniaceae)	Herb		EA	2000	3250
147	*Cynondon dactylon* (L.) Pers.	Poaceae	Gram		EA	1600	2700
148	*Cyperus aterrimus* Steud.	Cyperaceae	He		EA	1350	3350
149	*Cyperus bulbosus* Vahl	Cyperaceae	Herb		EA	0	2500
150	*Cyperus denudatus* L.f.	Cyperaceae	Gram		EA	1300	3650
151	*Cyperus fischerianus* Schimp. ex A.Rich.	Cyperaceae	Gram		EA	1700	2600
152	*Cyperus nutans* Vahl	Cyperaceae	Herb		EA	1300	3650
153	*Cyperus plateilema* (Steud.) Kuk.	Cyperaceae	Herb		EA	1800	3100
154	*Cyperus rigidifolius* Steud.	Cyperaceae	Herb		EA	1600	3100
155	*Cyphostemma molle* (Steud. ex Planch.) Desc.	Vitaceae	Herb		EE	200	2800
156	*Cytopteris fragilis* (L.) Bernh.	Woodsiaceae (Aspleniacea)	Ep		EA	2700	4000
157	*Danthonia subulata* A. Rich	Poaceae (Gramineae)	Gram		EE	3000	4300
158	*Debregeasia saeneb* (Forssk.) Hepper & J.R.I.Wood	Urticaceae	Shrub		EA	1500	2700
159	*Delphinium wellbyi* Hemsl.	Ranunculaceae	Herb		EA	2800	4300
160	*Deschampsia caespitosa* (L.) P. Beauv	Poaceae (Gramineae)	Gram		EA	2900	4000
161	*Deschampsia flexuosa* (L.) Trin	Poaceae (Gramineae)	Gram		EA	2800	4300
162	*Desmodium repandum* (Vahl.) DC.	Fabaceae (Leguminosae)	Herb/shrub		EA	2020	2460

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163	*Dianthoseris schimperi* Schultz-Bip. ex A. Rich.	Asteraceae (Compositae)	Herb		EA	3500	4500
164	*Dicrocephala integrifolia* (L.f.) O. Kuntze.	Asteraceae (Compositae)	Herb		EA	2014	2935
165	*Didymodoxa caffra* (Thunb.) Friis & Wilmot-Dear	Urticaceae	Herb		EA	1000	3000
166	*Dipsacus pinnatifidus* Steud. ex A. Rich.	Dipsacaceae	Herb		EA	1980	4100
167	*Discopodium penninervium* Hochst.	Solanaceae	Tree		EA	2532	2935
168	*Dodonaea angustifolia* L.f.	Sapindaceae	Shrub		EA	500	2900
169	*Dombeya torrida* (J. F. Gmel.) P. Bamps.	Sterculiaceae	Shrub/ tree		EA	1600	3100
170	*Dorstenia soerensenii* Friis	Moraceae	Herb		EA	1700	3000
171	*Dovyalis abyssinica* (A.Rich) Warb.	Flacourtiaceae	He		EA	1700	3000
172	*Dracaena afromontana* Mildbr	Dracaenaceae	Shrub/ tree		EA	1750	2800
173	*Drimia altissima* (L.f.) Ker-Gawl.	Hyacinthaceae	Herb		EA	3150	3450
174	*Droguetia iners* (Forssk.) Schweinf.	Urticaceae	Herb		EA	2060	3250
175	*Dryinaria volkensii* Hieron.	Polypodiaceae	Shrub		EA	2500	4200
176	*Dryopteris antarctica* (Bak.) C.chr.	Dryopteridaceae (Tectariaceae)	Ep		EA	1350	3000
177	*Dryopteris callolepis* C. Chr.	Dryopteridaceae (Tectariaceae)	EP		EA	2500	3320
178	*Dryopteris fadenii* Pic. Serm.	Dryopteridaceae (Tectariaceae)	Herb		EA	2500	2800
179	*Dryopteris inaequalis* (Schltdl.) Kuntze	Pteridaceae			EA	1500	2700
180	*Dryopteris kilemensis* (Kuhn) O. Kuntze.	Dryopteridaceae (Tectariaceae)	Herb		EA	1500	2700
181	*Dryopteris manniana* (Hook.) C. Chr.	Dryopteridaceae (Tectariaceae)	Herb		EA	3260	3300
182	*Echinops ellenbeckii* O. Hoffm.	Asteraceae (Compositae)	Shrub/tree	Yes	EE	2200	4000
183	*Echinops hoehnelii* Scweinf.	Asteraceae (Compositae)	Herb/shrub		EA	2830	3300
184	*Echinops longisetus* A. Rich.	Asteraceae (Compositae)	Herb/shrub	Yes	EE	2000	4000
185	*Echinops macrochaetus* Fresen.	Asteraceae (Compositae)	Herb		EA	1350	3600
186	*Elaphoglossum deckenii* (Kuhn) C.Ch.	Aspleniaceae (Lomariopsidaceae)	Ep		EA	1750	3400
187	*Embelia schimperi* Vatke	Myrsinaceae	Shrub/ tree		EA	1500	3500
188	*Epilobium stereophyllum* Fres.	Onagraceae	Herb		EA	1750	4300
189	*Erica arborea* L.	Ericaceae	Shrub/ tree		EA	2200	3900
190	*Erica trimera* (Engl.) Beentje.	Ericaceae	Shrub/ tree		EA	3200	4200
191	*Eriocaulon volkensii* Engl.	Eriocaulaceae	Shrub		EA	2950	3970
192	*Erodium moschatum* (L.) L'Herit. ex Ait.	Geraniaceae	Herb		EA	1200	3440
193	*Erophila verna* (L.) F. Chevall.	Brassicaceae (Cruciferae)	Herb		BE	3000	0
194	*Erucastrum meruense* Jonsell	Brassicaceae (Cruciferae)	Herb		BE	3000	3450
195	*Erythrina brucei* Schweinf. emend. Gillett	Fabaceae	Tree	Yes	EE	1400	2600

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196	*Eucalyptus globulus* Labill.	Myrtaceae	Tree		EA	1700	2800
197	*Euclea racemosa* Murr. ssp schimperi (A. DC.)	Ebenaceae	Shrub/ tree		EA	700	2935
198	*Euphorbia dumalis* S. Carter	Euphorbiaceae	Shrub		EE	2200	3660
199	*Euphorbia petitiana* A. Rich.	Euphorbiaceae	Herb		EA	2550	3650
200	*Euphorbia schimperiana* Scheele	Euphorbiaceae	Herb		EA	1350	3150
201	*Exotheca abyssinica* (Hochst ex A. Rich.) Anderss.	Poaceae (Gramineae)	Gram		EA	1700	3100
202	*Ferula communis* L.	Apiaceae (Umbelliferae)	Herb		EA	1400	3250
203	*Festuca abyssinica* Hochst. ex A. Rich.	Poaceae (Gramineae)	Gram		EA	2400	4000
204	*Festuca richardii* Alexeev	Poaceae (Gramineae)	Gram		EA	3800	4370
205	*Festuca simensis* Hochst. ex A. Rich	Poaceae (Gramineae)	Gram		EA	2600	3900
206	*Galium thunbergianum* Eckl. & Zeyh	Rubiaceae	Climber		EA	2200	3600
207	*Galium aparinoides* Frossk.	Rubiaceae	He		EA	2200	3600
208	*Galium hochstetteri* Pichi-Serm.	Rubiaceae	Herb		EA	2400	4400
209	*Galium simense* Fresen.	Rubiaceae	Herb		EA	1700	4000
210	*Galium spurium* L.	Rubiaceae	Herb		EA	1000	3000
211	*Geranium aculeotalum* Oliv.	Geraniaceae	Herb		EA	1200	3050
212	*Geranium arabicum* Forssk.	Geraniaceae	Herb		EA	1300	3650
213	*Geranium Sp.*	Geraniaceae	Herb		EE	4150	4200
214	*Gnaphalium rubriflorum* Hilliard	Asteraceae (Compositae)	Herb		EA	2000	3600
215	*Gnidia glauca* (Fresen.) Gilg.	Thymeleaceae	Shrub/ tree		EA	950	3200
216	*Gutenbergia rueppellii* Sch. Bip.	Asteraceae (Compositae)	Herb		EA	1200	2300
217	*Habenaria petitiana* (A. Rich.) Th. Dur. & Schinz	Orchidaceae	Herb		EA	1200	3150
218	*Hagenia abyssinica* (Bruce) J.F.Gmel.	Rosaceae	Tree		EA	2450	3250
219	*Haplocarpha rueppellii* (Schultz-Bip.) P. Beauv.	Asteraceae (Compositae)	Herb		EA	2440	4375
220	*Haplocarpha schimperi* (Schultz-Bip.) P. Beauv	Asteraceae (Compositae)	Herb		EA	2200	3660
221	*Haplosciadium abyssinicum* Hochst.	Apiaceae (Umbelliferae)	Herb		EA	2000	4300
222	*Hebenstreitia dentata* L.	Scrophulariaceae	Herb/shrub		EA	2300	4100
223	*Hebenstretia angolensis* Rolfe	Scrophulariaceae	Shrub		EA	2300	4100
224	*Helichrysum citrispinum* Del	Asteraceae (Compositae)	Herb/shrub		EA	3000	4500
225	*Helichrysum cymosum* (L.) Less.	Asteraceae (Compositae)	Herb		EA	2000	3750
226	*Helichrysum foetidum* (L.) Moench.	Asteraceae (Compositae)	Herb		EA	1500	3900
227	*Helichrysum formosissimum* Sch. Bip. ex A. Rich.	Asteraceae (Compositae)	Herb		EA	2050	4345
228	*Helichrysum forsskahlii* (J.F. Gmel) Hilliard & Burtt	Asteraceae (Compositae)	Herb		EA	3000	4370

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229	*Helichrysum gerberifolium* (Sch. Bip.) A. Rich.	Asteraceae (Compositae)	Herb		EA	1600	3200
230	*Helichrysum globosum* Schultz-Bip. ex A. Rich.	Asteraceae (Compositae)	Herb		EA	1350	3660
231	*Helichrysum gofense* Cufod	Asteraceae (Compositae)	Herb		EE	3275	4375
232	*Helichrysum harennensis* Mesfin	Asteraceae (Compositae)	Herb		EE	3200	3600
233	*Helichrysum horridum* (Sch. Bip.) A. Rich.	Asteraceae (Compositae)	Shrub	Yes	EE	2500	3600
234	*Helichrysum schimperi* (Schultz-Bip.) Moeser	Asteraceae (Compositae)	Herb/shrub		EA	1750	3300
235	*Helichrysum splendidum* (Thunb.) Less.	Asteraceae (Compositae)	Herb/shrub		EA	2500	4300
236	*Heracleum abyssinicum* (Boiss.) Norman	Apiaceae (Umbelliferae)	Herb		EA	1800	3750
237	*Heracleum alogonense* (Wolff) Norman	Apiaceae (Umbelliferae)	Herb		EA	2820	4150
238	*Hibiscus berberidifolius* A. Rich.	Malvaceae	Shrub		EA	1400	2650
239	*Hibiscus vitifolius* L.	Malvaceae	He		EA	200	2400
240	*Huperzia saururus* Lam.	Lycopodiaceae	Ep		EA	2500	3700
241	*Hydrocotyle mannii* Hook.f.	Apiaceae (Umbelliferae)	Herb		EA	1350	3750
242	*Hypericum revolutim* Vahl	Guttiferae (Clusiaceae, Hypericaceae)	Tree		EA	2250	3650
243	*Hypericum roeperanum* W.G. Schimp. ex. A. Rich.	Guttiferae (Clusiaceae, Hypericaceae)	Shrub/tree		EA	2000	3000
244	*Hypoestes forskaolii* (Vahl) R. Br.	Acanthaceae	Herb		EA	1950	2820
245	*Hypoestes triflora* (Forssk.) Roem. & Schult.	Acanthaceae	Herb		EA	1200	3200
246	*Hypolepis rugosula* (Lab.) var. africana C. Ch.	Hypolepidaceae (Aspleniacea)	Herb		EA	2500	4400
247	*Ilex mitis* (L.) Radlk.	Aquifoliaceae	Tree		EA	1980	2935
248	*Impatiens ethiopica* Grey-Wilson	Balsaminaceae	Herb		EA	1150	3200
249	*Impatiens rothii* Hook. f.	Balsaminaceae	Herb		EA	1600	3500
250	*Impatiens tinctoria subsp abyssinica* (Hook. f.) Grey.	Balsaminaceae	Herb		EA	1600	3500
251	*Indigofera arrecta* Hochst. ex A. Rich.	Leguminosae	Herb		EA	400	2700
252	*Inula confertiflora* A. Rich.	Asteraceae (Compositae)	shrub	yes	EE	2500	3700
253	*Inula macrophyllus* Sch. Bip. Ex. A. Rich.	Asteraceae (Compositae)	Herb		EA	1400	2600
254	*Ipomea oenotherae* (Vatke) hall. F.	Convolvulaceae	Herb		EA	1150	2400
255	*Isolepis setacea* (L.) R. Br.	Cyperaceae	Gram		EA	2300	4100
256	*Jasminum floribundum* R.Br. ex A. Rich	Oleaceae	Shrub		EA	1600	2800
257	*Jasminum abyssinicum* Hochst. ex. DC.	Oleaceae	Climber		EA	1700	2800
258	*Jasminum grandiflorum* L.	Oleaceae	Climber		EA	1600	2800
259	*Juniperus procera* Hochst. ex Endl.	Cupressaceae	Tree		EA	2090	3250
260	*Justicia schimperiana* (Hochst. Ex Nees) T. Anders.	Acanthaceae	Shrub		EA	1300	2700
261	*Kalanchoe petitiana* A. Rich	Crassulaceae	Herb		EE	2000	3000

No	*Species*	Family	Growth Form	Red List	Distribution and Endemism	Lower Range	Upper Range
262	*Kalanchoe schimperiana* A. Rich.	Crassulaceae	Subshrub		EA	2400	2700
263	*Kniphofia foliosa* Hochst	Asphodelaceae(Liliaceae)	Herb		EE	2500	4000
264	*Kniphofia isoetifolia* Hochst.	Asphodelaceae(Liliaceae)	Herb		EE	2050	3650
265	*Koeleria capensis* (Steud.) Nees	Poaceae (Gramineae)	Gram		EA	2500	4350
266	*Lactuca glandulifera* Hook.f.	Asteraceae (Compositae)	Herb		EA	3150	3450
267	*Laggera crispata* (Vahl) Hepper & J.R.I. Wood	Compositae	Herb		EA	350	2550
268	*Laggera tomentosa* Sch. Bip. ex A. Rich.	Compositae	Herb/shrub		EA	2345	2950
269	*Leonotis ocymifolia* (N. L. Burm.) Iwarsson	Lamiaceae (Labiatae)	Shrub		EA	500	3700
270	*Leucas stachydiformis* (Benth.) Hochst. ex Briq.	Lamiaceae	Shrub		EE	2400	3800
271	*Lobelia giberroa* Hemsl	Lobeliaceae	Herb		EA	1700	2800
272	*Lobelia rhynchopetalum* (Hochst.) Hemsl	Lobeliaceae	Herb		EE	3000	4350
273	*Lobelia scebelii* Chiov.	Lobeliaceae (Campanulaceae)	Herb		EE	1600	3100
274	*Lobelia schimperi* Hochst.ex. A. Rich	Lobeliaceae	Herb		EE	2400	3800
275	*Lotus discolor* E. Mey.	Fabaceae (Leguminosae)	Herb		EA	2000	4000
276	*Loxogramme abyssinica* (Baker) M.G. Price	Polypodiaceae	Fern		EA	2500	4300
277	*Luzula abyssinica* Parl.	Juncaceae	Herb		EA	2700	4100
278	*Luzula johnstonii* Buchen.	Juncaceae	Herb		EA	1600	3800
279	*Lysimachia ruhmeriana* Vatke	Primulaceae	Herb		EA	2000	4100
280	*Maesa lanceolata* Forssk.	Myrsinaceae	Shrub/ tree		EA	1500	3500
281	*Malva verticillata* L.	Malvaceae	Herb		EA	1600	4000
282	*Maytenus addat* (Loes.) Sebsebe	Celastraceae	Shrub	Yes	EE	2200	3100
283	*Maytenus arbutifolia* (A. Rich.) R. Wilczek	Celastraceae	Shrub/ tree		EA	1200	3100
284	*Maytenus gracilipes* (Welw. ex Oliv.) Sebsebe	Celastraceae	Shrub		EA	1250	2800
285	*Maytenus harenaensis* Sebsebe	Celastraceae	Shrub	Yes	BE	1600	3050
286	*Maytenus senegalesis* Lam.	Celastraceae	Tree/shrub		EA	380	2440
287	*Melia azedarach* L.	Meliaceae	tree		EA	0	2400
288	*Merendera abyssinica* A. Rich.	Liliaceae (Colchicaceae)	Herb		EA	2050	3880
289	*Merendera schimperiana* Hochst.	Colchicaceae (Liliaceae)	Herb		EA	2050	3880
290	*Minuaritia filitolia* (Forssk.) Mattf.	Caryophyllaceae	Herb		EA	1800	4050
291	*Momordica foetida* Schum & Thonn.	Cucurbitaceae	Herb		EA	530	3450
292	*Montia fontana* L. ssp. Fontana	Portulacaceae	Herb		EA	3950	4250
293	*Myosotis abyssinica* Boiss. & Reut.	Boraginaceae (Begoniaceae)	Herb		EA	2980	3590
294	*Myosotis keniensis* Th. Fr. Jr.	Boraginaceae (Begoniaceae)	Herb		EA	2800	3900

No	*Species*	Family	Growth Form	Red List	Distribution and Endemism	Lower Range	Upper Range
295	*Myosotis vestergrenii* Stroh.	Boraginaceae (Begoniaceae)	Herb		EA	3010	3600
296	*Myrsine africana* L.	Myrsinaceae	Tree		EA	2500	3750
297	*Myrsine melanophloeos* (L.) R. Br.	Myrsinaceae	Shrub/ tree		EA	2500	3750
298	*Neprophyllum abyssinicum* Hochst. ex A. Rich.	Convolvulaceae	Herb		EE	1650	2800
299	*Nuxia congesta* R. Br. ex Fresen.	Loganiaceae	Tree/shrub		EA	1100	3800
300	*Ocimum obovatum* E.Mey. ex Benth.	Lamiaceae	Herb		EA	2800	3400
301	*Oenanthe procumbens* (Wolff.) Norman	Apiaceae (Umbelliferae)	Herb		EA	2800	3400
302	*Oldenlandia monanthos* (A. Rich.) Hiern.	Rubiaceae	Herb		EA	1700	3500
303	*Olea africana* Mill.	Oleaceae	Tree		EA	1250	3000
304	*Olea hochstetteri* (Baker) Friis & P. S. Green	Oleaceae	Tree		EA	1350	3200
305	*Olea welwitschii* (Knobl.) Gilg & Schellenb.	Oleaceae	Tree		EA	1700	2500
306	*Olinia rochetiana* A. Juss.	Oliniaceae	Shrub/ tree		EA	1250	3500
307	*Oreophytum falcatum* (A. Rich.) O.E. Schulz.	Brassicaceae (Cruciferae)	He		EA	3820	4600
308	*Oxalis corniculata* L.	Oxalidaceae	Herb		EA	1000	3200
309	*Oxalis procumbens* Steud. Ex. A. Rich.	Oxalidaceae	Herb		EA	2650	3700
310	*Panicum hymeniochilum* Nees	Poaceae (Gramineae)	Gram		EA	1800	2400
311	*Parietaria debilis* G. Forster.	Urticaceae	Herb		EA	1350	3750
312	*Parochaetus communis* D. Don	Fabaceae (Leguminosae)	He		EA	1800	3500
313	*Pennisetum humile* Hochst. Ex A. Rich.	Poaceae (Gramineae)	Gram		EE	2800	4000
314	*Pennisetum thunbergii* Kunth	Poaceae (Gramineae)	Gram	Yes	EA	1700	4200
315	*pentaschistis borussica* (K. Schum.) Pilg.	Poaceae (Gramineae)	Gram		EA	2850	3980
316	*Pentaschistis pictigluma* (Steud.) Pilg.	Poaceae (Gramineae)	Gram		EA	2400	4300
317	*Periploca linearifolia* Quart. Dill. & A. Rich.	Asclepiadaceae	Liana		EA	600	2900
318	*Petridium aquilinium* (L.) Kuhn	Dennstaedtiaceae	Shrub		EA	500	3700
319	*Peucedanum winkleri* Wolff H	Apiaceae (Umbelliferae)	He		EA	1600	3700
320	*Phagnalon abyssinicum* Sch. Bip. ex. A. Rich.	Asteraceae (Compositae)	Herb		EE	1800	3660
321	*Phytolacca dodecandra* L'Herit.	Phytolaccaceae	Shrub		EA	1500	3000
322	*Pimpinella oreophila* Hoof.f.	Apiaceae (Umbelliferae)	Herb		EA	2150	4200
323	*Pittosporum viridiflorum* Sims	Pittosporaceae	Shrub/ tree		EA	1400	3000
324	*Plantago afra* L. var stricta (Schousboe) Maire	Plantaginaceae	Herb		EA	1800	4000
325	*Plantago lanceolata* L.	Plantaginaceae	Herb		EA	1200	3200
326	*Plantago palmata* Hook. F.	Plantaginaceae	Herb		EA	2150	3200
327	*Plectocephalus varians* (A. Rich.) C. Jeffrey ex Cuf.	Asteraceae (Compositae)	Herb		EE	1900	3600

No	*Species*	Family	Growth Form	Red List	Distribution and Endemism	Lower Range	Upper Range
328	*Plectranthus garckeanus* (Vatke.) J.K. Morton	Lamiaceae (Labiatae)	Herb		EA	2000	4000
329	*Plectranthus punctatus* (L.f.) LHer.	Lamiaceae (Labiatae)	Herb		EA	1350	3200
330	*Pleopeltis macrocarpa* (Bory ex Willd.) Kaulf.	Polypodiaceae (Aspleniacea)	Ep		EA	1700	3100
331	*Pluchea ovalis* (Pers.) DC.	Asteraceae (Compositae)	Shrub		EA	1500	4200
332	*Poa annua* L.	Poaceae (Gramineae)	Gram		EA	2400	4000
333	*Poa leptoclada* Hochst ex A. Rich.	Poaceae (Gramineae)	Gram		EA	2300	4050
334	*Poa muhavurensis* C. E. Hubb	Poaceae (Gramineae)	Gram		EA	4100	4300
335	*Poa schimperiana* Hochst. ex A. Rich.	Poaceae (Gramineae)	Gram		EA	1700	4050
336	*Poa simensis* Hochst. ex. A. Rich.	Poaceae (Gramineae)	Gram		EA	1200	4000
337	*Podocarpus falcatus* Mirb.	Podocarpaceae	Tree		EA	2120	2620
338	*Polygala steudneri* Chod.	Polygalaceae	Herb		EA	2500	4000
339	*Polypogon Schimperianus* (Hochst. ex. Steud.) Cope	Poaceae (Gramineae)	Gram		EA	2800	3750
340	*Polystichum fuscopaleaceum* Alston	Dryopteridaceae (Tectariaceae)	Ep		EA	2600	4300
341	*Polystichum volkensii* (Hieron.) C.Chr.	Dryopteridaceae (Tectariaceae)	He		EA	2800	3600
342	*Potentilla dentata* Forsk.	Rosaceae	Herb		EA	2600	3900
343	*Prenanthes subpeltata* Stebbins	Asteraceae (Compositae)	Herb		EA	1700	2950
344	*Protea gaguedi* J.F. Gmel.	Proteaceae	Shrub/tree		EA	1400	3000
345	*Prunus africana* (Hook.f.) Kalkm.	Rosaceae	Tree		EA	1750	3350
346	*Pseudognaphalium richardianum* (Cuf.) Hilliard & Butt.	Asteraceae (Compositae)	Herb		EA	2100	3200
347	*Ranunculus Simensis* Fresen.	Ranunculaceae	Herb		EE	2400	3150
348	*Ranunculus stagnalis* Hochst. ex A. Rich.	Ranunculaceae	Herb		EA	2250	4100
349	*Ranunculus volkensii* Engl.	Ranunculaceae	Herb		EA	2880	3200
350	*Rapanea simensis* Hochst. ex DC.	Myrsinaceae	Shrub/tree		EA	2500	3750
351	*Rhamnus prinoides* L'Herit.	Rhamnaceae	Shrub/tree		EA	1175	3200
352	*Rosa abyssinica* Lindley	Rosaceae	Shrub		EA	1900	3300
353	*Rubia cordifolia* L.	Rubiaceae	Herb		EA	1800	2600
354	*Rubus pinnatus* Willd.	Rosaceae	Shrub		EA	2300	3050
355	*Rubus steudneri* Schweinf	Rosaceae	Shrub		EA	2300	3050
356	*Rumex abyssinicus* Jacq.	Polygonaceae	Herb		EA	1200	3300
357	*Rumex bequaertii* De Wild.	Polygonaceae	Herb		EA	3000	3240
358	*Rumex nepalensis* Spreng.	Polygonaceae	Herb		EA	1200	3900
359	*Sagina abyssinica* A. Rich.	Caryophyllaceae	Herb		EE	2150	3400
360	*Sagina afroalpina* Hedb.	Caryophyllaceae	Herb		EA	2980	4000

No	*Species*	Family	Growth Form	Red List	Distribution and Endemism	Lower Range	Upper Range
361	*Salvia merjamie* Forssk.	Lamiaceae (Labiatae)	Herb		EA	2500	4200
362	*Salvia schimperi* Benth.	Lamiaceae (Labiatae)	Herb		EA	1800	3200
363	*Sanicula elata* Buch. Ham. ex D. Don.	Apiaceae (Umbelliferae)	Herb		EA	300	3500
364	*Satureja imbricata* (Forssk.) Briq.	Lamiaceae (Labiatae)	Shrub		EA	2500	4300
365	*Satureja kilimandschari* (Gürke) Hedb.	Lamiaceae (Labiatae)	Herb		EA	4000	4140
366	*Satureja paradoxa* (Vatke) Engl. ex Seybold	Lamiaceae (Labiatae)	Herb		EE	1350	3500
367	*Satureja pseudosimensis* Brenan	Lamiaceae (Labiatae)	Herb		EA	2500	4200
368	*Satureja punctata* (Benth.) Briq. ssp. Punctata	Lamiaceae (Labiatae)	Shrub		EA	600	3840
369	*Satureja simensis* (Benth.) Briq.	Lamiaceae (Labiatae)	Herb		EE	1900	4100
370	*Scabiosa columbaria* L.	Dipsacaceae	Herb		EA	2000	4100
371	*Schefflera volkensii* (Engl.) Harms	Araliaceae	Tree		EA	1600	3250
372	*Schrebera alata* (Hochst.) Welw.	Oleaceae	Shrub/tree		EA	1500	2500
373	*Sedum baleensis* M. Gilbert.	Crassulaceae	Herb		EE	2700	3400
374	*Sedum churchillianum* Robyns & Boutique	Crassulaceae	Herb		EA	3150	4050
375	*Sedum crassularia* Raym. Hamet.	Crassulaceae	Herb		EA	3700	4350
376	*Sedum mooneyi* M. Gilbert	Crassulaceae	Herb		EE	3400	4100
377	*Selagnella kraussiana* (Kunze) A. Br.	Selaginellaceae	Herb		EA	2340	3150
378	*Senecio mannii* Hook.f.	Asteraceae (Compositae)	Herb		EE	1520	4300
379	*Senecio fresenii* Sch. Bip. ex Oliv. & Hiern	Asteraceae (Compositae)	Herb		EE	1520	4300
380	*Senecio inornatus* DC.	Asteraceae (Compositae)	Herb		EA	1520	3500
381	*Senecio myriocephalus* Sch. Bip. Ex A. Rich	Asteraceae (Compositae)	Shrub		EE	2250	2900
382	*Senecio nanus* Schultz-Bip. Ex. A.Rich.	Asteraceae (Compositae)	Herb		EE	3250	4100
383	*Senecio ochrocarpus* Oliv. & Hiern	Asteraceae (Compositae)	Herb		EE	2800	4300
384	*Senecio ragazzi* Chiov.	Asteraceae (Compositae)	Herb		EA	2700	3900
385	*Senecio schimperi* Sch.Bip. ex A. Rich.	Asteraceae (Compositae)	Herb		EE	3900	4375
386	*Senecio schultzii* Hochst. ex A. Rich.	Asteraceae (Compositae)	Herb		EE	3270	4375
387	*Senecio steudelii* Sch. Bip. Ex A.Rich.	Asteraceae (Compositae)	Herb		EE	2000	3300
388	*Senecio subsessilis* Oliv. & Hiern	Asteraceae (Compositae)	Herb		EA	2400	4310
389	*Senecio unionis* Schultz-Bip. ex. A. Rich.	Asteraceae (Compositae)	Herb		EE	3170	4050
390	*Sida abyssinica* Hochst ex. D. Dietr.	Malvaceae	Herb		EA	2650	3700
391	*Sida schimperiana* Hochst ex A. Rich.	Malvaceae	Shrub		EA	1500	2600
392	*Silene macrosolen* Steud. ex A.Rich.	Caryophyllaceae	Herb		EA	1900	3600
393	*Sinarundinaria alpina* (K. Schum.) Chao & Renv.	Poaceae (Gramineae)	Gram		EA	1750	3350

No	*Species*	Family	Growth Form	Red List	Distribution and Endemism	Lower Range	Upper Range
394	*Solanecio angulatus* (Vahl) C. Jeffrey	Asteraceae (Compositae)	Climber		EA	1750	3350
395	*Solanecio gigas* (Vatke). C. Jeffrey	Asteraceae (Compositae)	Shrub/tree	yes	EE	1750	3350
396	*Solanecio mannii* (Hook.f.) C. Jeffrey	Asteraceae (Compositae)	Shrub/tree		EA	1300	2450
397	*Solanecio tuberosus* (Sch. Bip. Ex. A. Rich) C. Jeffrey	Asteraceae (Compositae)	Herb		EA	1600	2500
398	*Solanum benderianum* Schimper ex. Damme	Solanaceae	Shrub		EA	2300	3500
399	*Solanum anguivi* Lam.	Solanaceae	Herb		EA	1742	2935
400	*Solanum hirtulum* Steud. ex. A. Rich.	Solanaceae	Herb		EE	2250	3230
401	*Solanum incanum* L.	Solanaceae	shrub		EE	2100	3300
402	*Solanum macracanthum* A. Rich	Solanaceae	Shrub		EA	2000	3100
402	*Solanum marginatum* L.f.	Solanaceae	Herb		EA	700	2350
403	*Solanum nigrum* L.	Asteraceae (Compositae)	Herb		EA	1650	2440
404	*Sonchus bipontini* Aschers	Asteraceae (Compositae)	Herb		EA	2400	4100
405	*Sonchus melanolepis* Fresen.	Asteraceae (Compositae)	Herb		EA	1650	2440
406	*Sonchus oleraceus* L.	Asteraceae (Compositae)	Herb		EA	1650	2440
407	*Stachys aculeolata* Hook. F.	Lamiaceae (Labiatae)	Herb		EA	1200	3500
408	*Stachys alpigena* T. C. E. Fries.	Lamiaceae (Labiatae)	Herb		EE	1750	3800
409	*Stellaria sennii* Chiov.	Caryophyllaceae	Herb		EA	1300	3500
410	*Stephania abyssinica* (Dillion ex A. Rich.) Walp	Menispermaceae (Melianthaceae)	Herb		EA	1450	3400
411	*Subularia monticola* Schweinf.	Brassicaceae (Cruciferae)	Herb		EA	3100	4300
412	*Swertia engleri* Gilg. Var engleri	Gentianaceae	Herb		EA	3350	4500
413	*Swertia kilimandscharica* Engl.	Gentianaceae	Herb		EA	2450	3840
414	*Swertia pumila* Hochst.	Gentianaceae	Herb		EE	3050	3750
415	*Swertia schimperi* (Hochst) Griseb.	Gentianaceae	Herb		EA	1400	3900
416	*Syzygium guineense* (Willd.) DC.	Myrtaceae	Tree		EA	1580	2450
417	*Teclea nobilis* Del.	Rutaceae	Shrub/ tree		EA	900	2750
418	*Thalictrum rhynchocarpum* Dillon & A. Rich.	Ranunculaceae	Herb		EA	1600	3050
419	*Thesium kilimandscharicum* Engl.	Santalaceae	Herb/shrub		EA	2950	4000
420	*Thlaspi alliaceum* (L.)	Brassicaceae (Cruciferae)	Herb		EA	3150	4620
421	*Thymus schimperi* Ronniger	Lamiaceae (Labiatae)	Herb		EE	2250	4000
422	*Toddalia asiatica* (L.) Lam.	Rutaceae	Climber		EA	550	3300
423	*Trichomanes inopinatum* (Pichi-Serm.) Kornas	Hymenophylaceae (Aspleniacea)	Ep		EA	1100	2650
424	*Trichomanes melanotrichum* Schlecht.	Hymenophylaceae (Aspleniacea)	Ep		EA	1100	2650
425	*Tridax procumbens* L.	Asteraceae (Compositae)	Herb		EA		

No	*Species*	Family	Growth Form	Red List	Distribution and Endemism	Lower Range	Upper Range
426	*Trifolium acaule* Steud ex A. Rich.	Fabaceae (Leguminosae)	Herb		EA	2500	4150
427	*Trifolium burchellianum* Ser. ssp. johnstonii (Oliv.) Gillett.	Fabaceae (Leguminosae)	Herb		EA	2200	3980
428	*Trifolium cryptopodium* A. Rich.	Fabaceae	Herb		EA	2000	4300
429	*Trifolium semipilosum* Fresen.	Fabaceae (Leguminosae)	Herb		EA	1800	3150
430	*Trifolium simensis* Fresen.	Fabaceae (Leguminosae)	Herb		EA	1780	3800
431	*Trifolium spananthum* M. Thulin	Fabaceae (Leguminosae)	Herb		EE	2250	3900
432	*Trifolium tembrense* Fresen.	Fabaceae (Leguminosae)	Herb		EA	2300	3800
433	*Uebelina kiwuensis*	Caryophyllaceae	Herb		EA	1800	3800
435	*Umbilicus botryoides* A. Rich.	Crassulaceae	Herb		EA	2400	4150
436	*Urera hypselodendron* (A.Rich.) Wedd.	Urticaceae	Shrub		EA	1700	2800
437	*Urtica simensis* Hochst ex. A. Rich.	Urticaceae	Herb		EE	2200	4100
438	*Vallerianelea microcarpa* Loiseleur	Valerianaceae	Herb		EA	2200	4100
439	*Vallerianella microcarpa* Loiseleur	Valerianaceae	Herb		EA	2200	4100
440	*Verbascum floccosum* (Benth.) Kuntze	Scrophulariaceae	Herb		EA	2200	3980
441	*Verbascum sinaiticum* Benth.	Scrophulariaceae	He		EA	900	3300
442	*Vernonia hochstetteri* Sch. Bip. var. Hochstetteri	Asteraceaea (Compositae)	Shrub		EA	1200	3000
443	*Vernonia hymenolepis* A. Rich	Asteraceae (Compositae)	Shrub/tree		EA	1200	3000
444	*Vernonia myriantha* Hook.f.	Compositae	Tree		EA	700	2900
445	*Vernonia rueppellii* Sch.Bip. ex Walp.	Asteraceae (Compositae)	Sh		EE	2150	3000
446	*Veronica abyssinica* Fresen.	Scrophulariaceae	Herb		EA	2120	3400
447	*Veronica glandulosa* Hochst.ex Benth.	Scrophulariaceae	Herb		EA	2850	3980
448	*Veronica gunae* Engl.	Scrophulariaceae	Herb		EA	3700	4300
449	*Wahlenbergia pusilla* Hochst. ex A. Rich.	Campanulaceae	Herb		EA	2500	4500
450	*Wahlenbergia silenoids* Hochst. ex A. Rich.	Campanulaceae	Herb		EA	1800	3500
451	*Withania somnifera* (L.) Dunal	Solanaceae	Shrub		EA	600	2700
452	*Xiphopteris flabelliformis* (Poiret) Schelpe.	Grammitidaceae (Aspleniacea)	Ep		EA	2700	3400
453	*Zeheneria scabra* (Linn. F.) Sond.	Cucurbitaceae	Herb		EA	1200	3580

Appendix II

Supplementary materials for the research paper:

Ericaceous vegetation of the Bale Mountains of Ethiopia will prevail in the face of climate change

Yohannes O Kidane*[1], Samuel Hoffmann[1], Anja Jaeschke[1], Mirela Beloiu[1,4], Carl Beierkuhnlein [1,2,3]

[1] Department of Biogeography, Bayreuth, University of Bayreuth, Germany
[2] Bayreuth Center of Ecology and Environmental Research (BayCEER), Bayreuth, Germany
[3] Geographical Institute Bayreuth (GIB), Bayreuth, Germany
[4] Institute of Terrestrial Ecosystems, Department of Environmental System Sciences, ETH Zurich, Zurich, Switzerland
* **Corresponding Author**

Attachment I: R-Script

1. Predictor variables downloading and collinearity test

```
# Download environmental predictor variables from Worldclim
bio <- getData("worldclim", var="bio", res=0.5, lon=39, lat=6)
Download the usdam package
library (usdm)
# Test data set for collinearity. We used VIFcor to select the predictor variables those predictors
with value above 0.9 will automatically remove from the data set.
V <- vifcor(bio, th=0.9)
```

2. Data uploading and preprocessing.

```
install.packages(c("gdata", "pROC", "Rcpp", "tibble", "repos"))
setwd("C:/----)
library(dismo)
file <- paste(system.file(package="dismo"), "/ex/current/erica.csv", sep="")
file
# read the species occurrence table
erica <- read.table(file, header=TRUE, sep=",")
# read and inspect the values of the file# first rows
head(erica)
# Take the columns latitude and longitude of the occurrence points
erica <- erica[, 2:3]
#select the records that have longitude and latitude data
colnames(erica)
acgeo <- subset(erica, !is.na(lon) & !is.na(lat))
dim(acgeo)
# show some values
acgeo[1:2, c(1:2)]
library(maptools)
data(wrld_simpl)
plot(wrld_simpl, xlim=c(39.58, 40), ylim=c(6.65, 7.1), axes=TRUE, col="skyblue1")
# restore the box around the map
box()
# plot points to visualize the species occuren points
points acgeo$lon, acgeo$lat, col='blue4', pch=21, cex=0.5)
# managing duplicate entries by species
dups2 <- duplicated(acgeo[, c('lon', 'lat')])
# Identify the number of duplicates and removes them from the record
sum(dups2)
[1] 45
# Save the records that are not duplicated
acg <- acgeo[!dups2, ]
```

3. Cross checking

```
#Spatial Points Data Frame was built using the statistical function notation
library(sp)
coordinates(acg) <- ~lon + lat
crs(acg) <- crs(wrld_simpl)
class(acg)
# to use the coordinates to do a spatial query of the polygons in wrldsimpl (a SpatialPolygons
DataFrame)
class(wrld_simpl)
ovr <- over(acg, wrld_simpl)
head(ovr)
tail(ovr)
cntr <- ovr$NAME
i <- which(is.na(cntr))
j <- which(cntr != acg$country)
# for the mismatches, bind the country names of the polygons and points
cbind(cntr, acg$country)[j,]
r <- raster(acg)
points(acg[j, ], col='red', pch=20, cex=0.6)
```

4. Sampling bias

```
# create a RasterLayer with the extent of acgeo
r <- raster(acg)
# set the resolution of the cells to (for example) 1 degree
res(r) <- 0.055
# expand (extend) the extent of the RasterLayer a little
r <- extend(r, extent(r)+0.05)
# sample:
acsel <- gridSample(acg, r, n=0.05)
# to illustrate the method and show the result
p <- rasterToPolygons(r)
plot(p, border='skyblue3', legend=T)
points(acg, col='blue', pch=21, cex=0.5)
# selected points in red
points(acsel, cex=1, col='red', pch = 21)
legend(39.825, 7.07, legend=c("presence sampling points", "Subsampling points"),
       col=c("blue", "red"), pch=21:21, cex=0.7,
       box.lty=1, box.lwd=1, box.col="skyblue3")
```

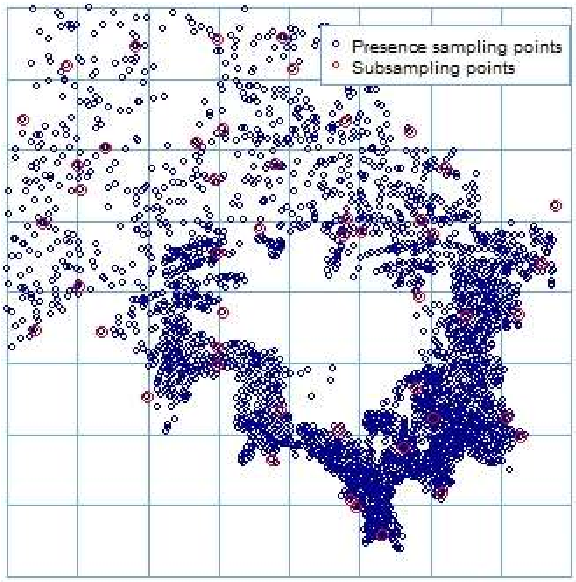


Figure 1: The presence (Navyblue) and subsampling (Red) points. Subsampling uses to reduce sampling biases. It is prepared using the grid sample function, which did a "chess-board" sampling. This is useful to split the data into "training" and "testing" data set records.

5. Absence and background points

```
#get the file names
files <- list.files(path=paste(system.file(package="dismo"), '/ex/current/', sep=''),
pattern='tif', full.names=TRUE )
#we use the first file to create a RasterLayer
mask <- raster(files[1])
#select 1500 random points set seed to assure that the examples will always have the same random
sample.
set.seed(1963)
bg <- randomPoints(mask, 1500 )
# set up the plotting area for two maps
par(mfrow=c(1,2))
plot(!is.na(mask), legend=F)
points(bg, cex=0.5)
#now we repeat the sampling but limit the area of sampling using a spatial extent. The ‘extent’
function further restricts the area from which random locations were drawn.
e <- extent(39.55, 39.99, 6.65, 7.1)
bg2 <- randomPoints(mask, 700, ext=e)
plot(!is.na(mask), legend=F)
plot(e, add=TRUE, col='red')
points(bg2, cex=0.5)
```

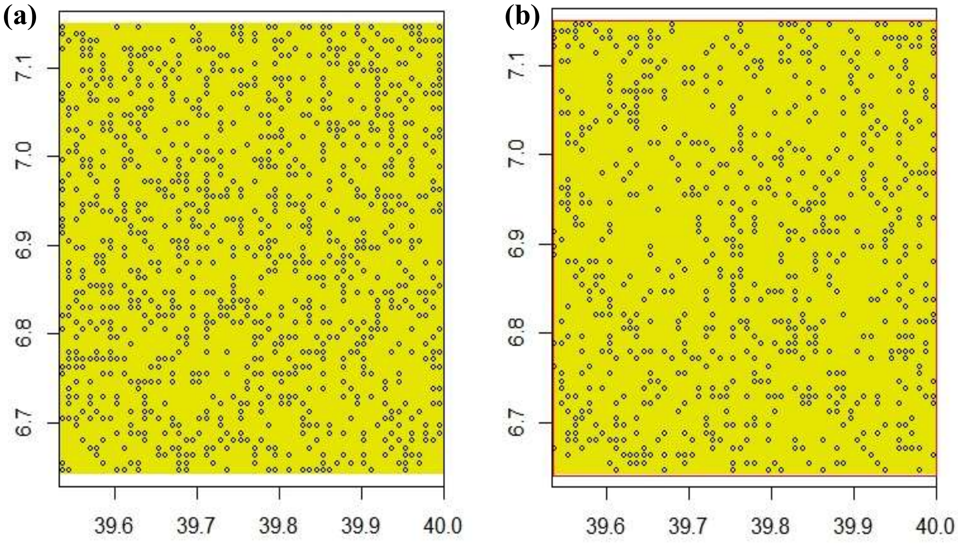


Figure 2: a) Randomly selected 1500 random points set.seed to assure that the examples will always have the same random sample. b) Sampled 700 random background points that were used to characterize and establishes the environmental domain of the study area.

```
file <- paste(system.file(package="dismo"), '/ex/current/erica.csv', sep='')
ac <- read.csv(file)
head(ac)
#ac is a data.frame. It must be changed into a Spatial Points Data Frame
coordinates(ac) <- ~lon+lat
projection(ac) <- CRS('+proj=longlat +datum=WGS84')
install.packages("rgeos")
# We create a 'circles' model using an arbitrary radius of 0.5 km
x <- circles(ac, d=500, lonlat=TRUE)
pol <- polygons(x)
# sample randomly from all circles
samp1 <- spsample(pol, 1500, type='random', iter=25) #iter=25
# get unique cells
cells <- cellFromXY(mask, samp1)
length(cells)
cells <- unique(cells)
length(cells)
xy <- xyFromCell(mask, cells)
plot(pol, axes=TRUE)
points(xy, cex=0.5, pch=20, col='blue4')
```

```
xy <- xyFromCell(mask, cells)
#Plot to inspect the results:
spxy <- SpatialPoints(xy, proj4string=CRS('+proj=longlat +datum=WGS84'))
o <- over(spxy, geometry(x))
xyInside <- xy[!is.na(o), ]
# extract cell numbers for the circles
v <- extract(mask, x@polygons, cellnumbers=T)
# use rbind to combine the elements in list v
v <- do.call(rbind, v)
# get unique cell numbers from which you could sample
v <- unique(v[,1])
head(v)
# to display the results
m <- mask
m[] <- NA
m[v] <- 1
plot(m, ext=extent(x@polygons)+ 1)
plot(x@polygons, add=T)
```

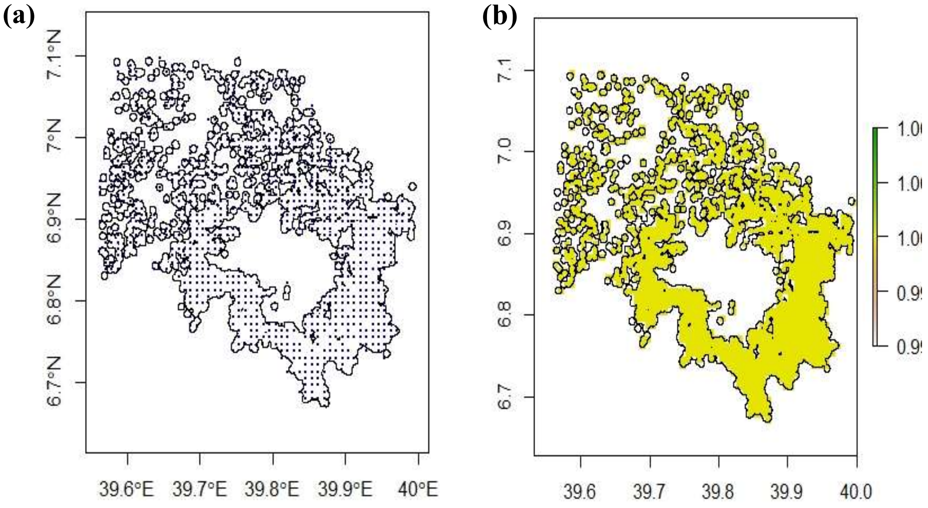


Figure 3: The species occurrence points were converted into spatial points data frame: a) overlaid on the background points and occurrence circle model of an arbitrary radius of 500m. The circles were 'dissolved' using rgeos package, b) The species occurrence points were converted to raster using the raster function.

6. Environmental data entry

```
files <- list.files(path=paste(system.file(package="dismo"), '/ex/current/', sep=''),
pattern='tif', full.names=TRUE )
files
predictors <- stack(files)
predictors
names(predictors)
plot(predictors)
library(maptools)
data(wrld_simpl)
file <- paste(system.file(package="dismo"), "/ex/current/erica.csv", sep="")
erica <- read.table(file,  header=TRUE,  sep=',')
plot(predictors, 1)
plot(wrld_simpl, add=TRUE)
# with the points function, "add" is implicit
points(erica, cex=0.5, pch=21, col='blue4')
```

7. Extracting values from raster

```
presvals <- extract(predictors, erica)
#setting random seed to always create the same random set of points for this example
list (predictors)
set.seed(0)
backgr <- randomPoints(predictors, 1500)
absvals <- extract(predictors, backgr)
pb <- c(rep(1, nrow(presvals)), rep(0, nrow(absvals)))
sdmdata <- data.frame(cbind(pb, rbind(presvals, absvals)))
head(sdmdata)
tail(sdmdata)
summary(sdmdata)
#pairs plot of the values of the climate data at the Erica occurrence sites.
pairs(sdmdata[,2:5], cex=0.2, fig=TRUE)
```

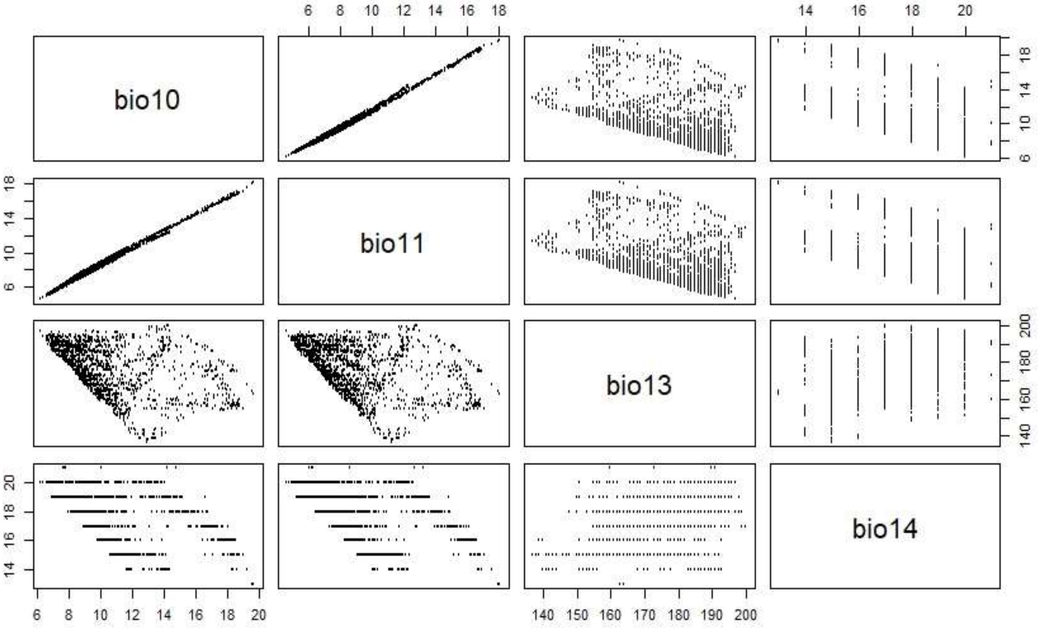


Figure 4: A pairs plot of environmental predictor variables at the Erica occurrence points (sites). The pair plot enables us to visually investigate collinearity in the environmental data (at the presence and background points).

8. Model fitting, prediction, and evaluation

a. Model fitting

```
m <- glm(pb ~ bio11 + bio13 + bio14, data=sdmdata)
class(m)
summary(m)
m2 = glm(pb ~ ., data=sdmdata)
m2
bc <- bioclim(sdmdata[,c('bio11', 'bio13', 'bio14')])
class(bc)
bc
pairs(bc)
```

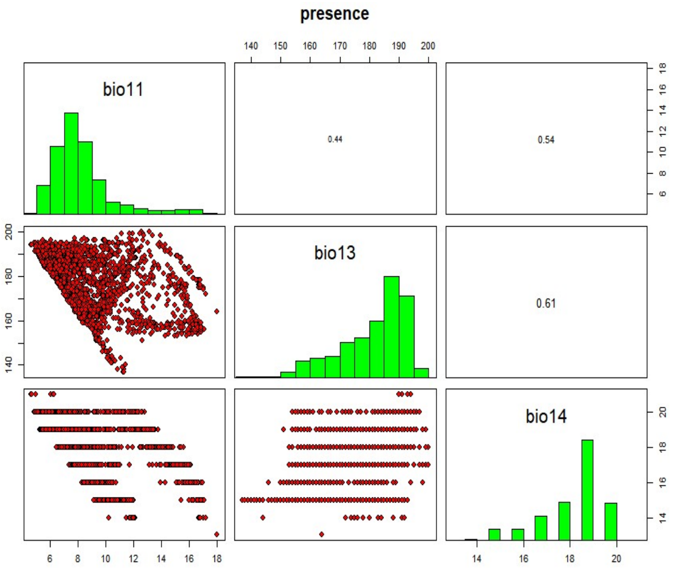


Figure 5: The fitted model which was carried out using only presence value using the 'prevals' function.

b. Model prediction

```
bio11 = c(40, 60, 5)
bio13 = c(150, 115, 15)
bio14 = c(200, 290, 30)
pd = data.frame(cbind(bio11, bio13, bio14))
pd
predict(m, pd)
predict(bc, pd)
response(bc)
names(predictors)
p <- predict(predictors, m)
plot(p) #main="Stacked predictors")
points(erica, cex=0.5, pch=21, col='blue4')
```

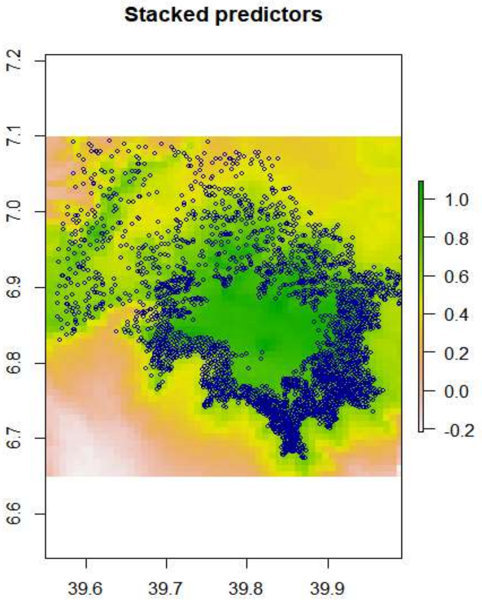


Figure 6: Layer stacked predictors variables with Erica occurrence point. This is suitability scores map created by the predict function with a Raster object and a model object.

c. Model evaluation

```
p <- rnorm(700, mean=0.7, sd=0.3)
a <- rnorm(700, mean=0.4, sd=0.4)
par(mfrow=c(1,2))
plot(sort(p), col='red', pch=21)
points(sort(a), col='blue', pch=21)
legend(1, 0.95 * max(a,p), c('precence', 'absence'),
       pch=c(21,21), col=c('red', 'blue'))
comb = c(p,a)
```

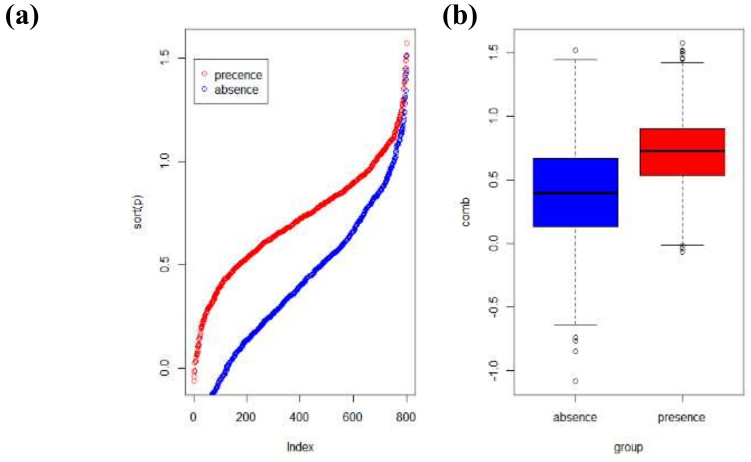


Figure 7: a) Correlation coefficient with two random variables presence((P) has higher values) and represents the predicted value for 700 known locations where the species is present, and absence (a) has lower values, and represents the predicted value for 700 known locations where the species is absent. **b)** box plot of Correlation coefficient.

```
samp <- sample(nrow(sdmdata), round(0.5 * nrow(sdmdata)))
traindata <- sdmdata[samp,]
traindata <- traindata[traindata[,1] == 1, 2:11]
testdata <- sdmdata[-samp,]
bc <- bioclim(traindata)
e <- evaluate(testdata[testdata==1,], testdata[testdata==0,], bc)
e
plot(e, 'ROC')
```

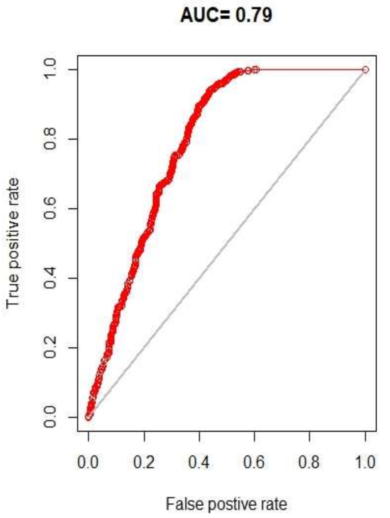


Figure 8: The presence data was divided into two random sets, one for training the models, and one for evaluating the model. The Area Under the Curve (AUC) was calculated. AUC=0.79 indicates that our model has high predicted suitability.

NB: *In our models the spatial sorting bias of the Area Under the Curve (AUC) was removed. The AUC value used was corrected.*

NB: 1. the dismo function K-fold data partitioning was used. It creates a vector that assigns each row in the data matrix to a group (between 1 to k). 2. The spatial sorting bias of the Area Under the Curve (AUC) was removed. The AUC value used was corrected.

```
pres <- sdmdata[sdmdata[,1] == 1, 2:11]
back <- sdmdata[sdmdata[,1] == 0, 2:11]
list (pres)
k <- 5
group <- kfold(pres, k)
group[2:11]
unique(group)
e <- list()
for (i in 1:k) {train <- pres[group != i,] test <- pres[group == i,]
  bc <- bioclim(train) e[[i]] <- evaluate(p=test, a=back, bc)}
auc <- sapply(e, function(x){slot(x, 'auc')} )
auc
mean(auc)
sapply( e, function(x){x@auc})
```

9. Types of algorithms & data used in examples.

```
files <- list.files(path(system.file(package="dismo"), '/ex/current/', sep=''), pattern='tif',
full.names=TRUE )
predictors <- stack(files)
file <- paste(system.file(package="dismo"), "/ex/current/erica.csv", sep="")
erica <- read.table(file, header=TRUE, sep=',')
erica <- erica [,-1]
presvals <- extract(predictors, erica)
set.seed(0)
backgr <- randomPoints(predictors, 1500)
absvals <- extract(predictors, backgr)
pb <- c(rep(1, nrow(presvals)), rep(0, nrow(absvals)))
sdmdata <- data.frame(cbind(pb, rbind(presvals, absvals)))
pred_nf <- dropLayer(predictors)
group <- kfold(erica, 5)
pres_train <- erica [group!= 1, ]
pres_test <- erica[group == 1, ]
ext = extent(39.55, 39.99, 6.65, 7.1)
backg <- randomPoints(pred_nf, n=1500, ext=ext, extf = 1.25)
colnames(backg) = c('lon', 'lat')
group <- kfold(backg, 5)
backg_train <- backg[group!= 1, ]
backg_test <- backg[group == 1, ]
r = raster(pred_nf, 1)
plot(!is.na(r), col=c('white', 'white4'), legend=F)
colors()
plot(ext, add=TRUE, col='red', lwd=1)
points(backg_train, pch=21, cex=0.4, col='green3')
points(backg_test, pch=21, cex=0.4, col='black')
points(pres_train, pch=21, cex=0.4, col='blue2')
points(pres_test, pch=21,cex=0.4, col='red')
legend(39.58, 6.75, legend=c("Backg train", "Backg test", "Presence train", "Presence test"),
col=c("green3", "black", "blue2", "red"), pch=20, cex=0.6, box.lty=1, box.lwd=1, box.col="red")
#lty=1,
```

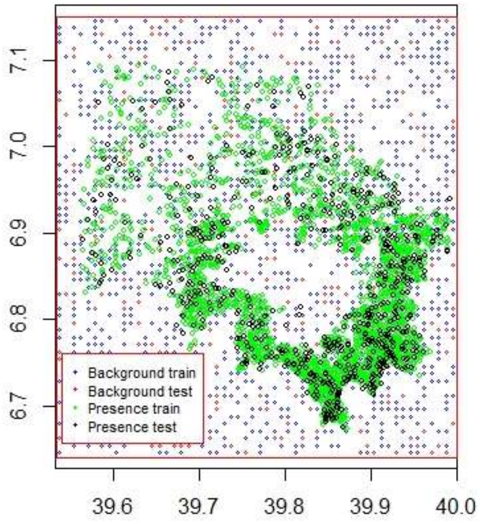


Figure 9: The Erica occurrence points (green) over laid on the stacked environmental variables, from which presence training and testing data sets, and background training and testing data sets were established.

NB: The random points only occur within the spatial extent of the rasters, and within cells that are not NA, and that there is only a single absence point per cell. Here the background points were restricted to be within 12.5% of the specified extent 'ext'.

10. Models

a. Bioclim

```
bc <- bioclim(pred_nf, pres_train)
plot(bc, a=1, b=2, p=0.85)
e <- evaluate(pres_test, backg_test, bc, pred_nf)
tr <- threshold(e, 'spec_sens')
pb <- predict(pred_nf, bc, ext=ext, progress='')
par(mfrow=c(1,2))
plot(pb, main='Bioclim Current')
plot(wrld_simpl, add=TRUE, border='dark gray')
plot(pb > tr, main='presence/absence')
plot(wrld_simpl, add=TRUE, border='dark grey')
points(pres_train, pch= 21, cex=0.6, col='black')
points(backg_train, pch='-', cex=0.5)
```

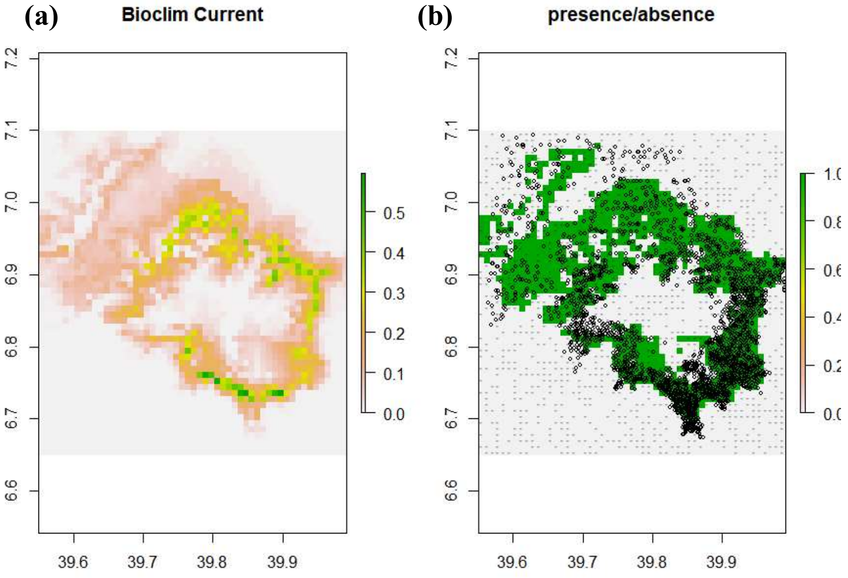


Figure 10: a) Bioclim current distribution range suitability scores map.
b) The prediction map that was subjectively classified into
presence (green) /absence (gray) (threshold=0.62).

b. Domain

```
dm <- domain(pred_nf, pres_train)
ed <- evaluate(pres_test, backg_test, dm, pred_nf)
pd = predict(pred_nf, dm, ext=ext, progress='')
par(mfrow=c(1,2))
plot(pd, main='Domain Current')
plot(wrld_simpl, add=TRUE, border='dark grey')
tr <- threshold(ed, 'spec_sens')
plot(pd > tr, main='presence/absence')
plot(wrld_simpl, add=TRUE, border='dark grey')
points(pres_train, pch= 21, cex=0.6, col='black')
points(backg_train, pch='-', cex=0.5)
```

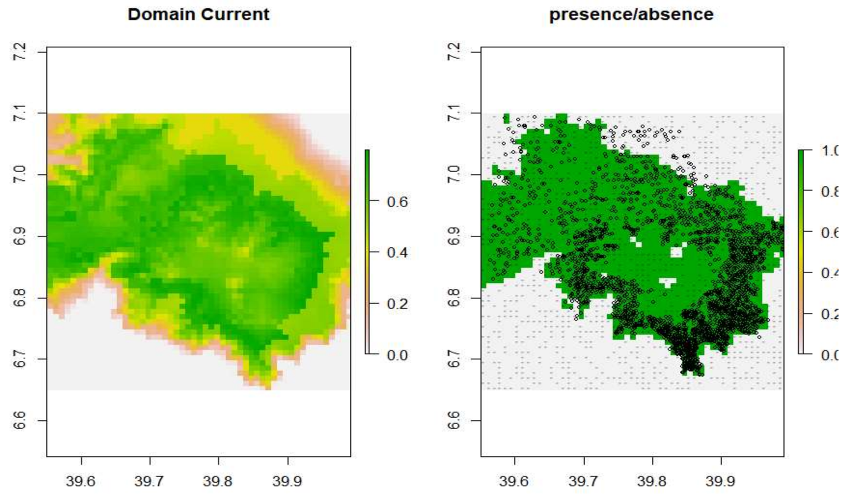


Figure 11: a) Domain **c**urrent distribution range suitability scores map.
b) The prediction map that was subjectively classified into presence (green) /absence (gray) (threshold=0.51).

c. Generalized Linear Models (GLMs).

```
train <- rbind(pres_train, backg_train)
pb_train <- c(rep(1, nrow(pres_train)), rep(0, nrow(backg_train)))
envtrain <- extract(predictors, train)
envtrain <- data.frame( cbind(pa=pb_train, envtrain) )
envtrain[,'bioclim'] = factor(envtrain[,'bioclim'], levels=2:11)
head(envtrain)
testpres <- data.frame( extract(predictors, pres_test) )
testbackg <- data.frame( extract(predictors, backg_test) )
family = binomial(link = "logit")
family = gaussian(link = "identity")
family = poisson(link = "log")

gm1 <- glm(pa ~ bio2 + bio8 + bio9 + bio11 + bio13 + bio14 + bio15 + bio18 + bio19, family =
binomial(link = "logit"), data=envtrain)
summary(gm1)
coef(gm1)
gm2 <- glm(pa ~ bio2 + bio8 + bio9 + bio11 + bio13 + bio14 + bio15 + bio18 + bio19, family =
gaussian(link = "identity"), data=envtrain)
valuate(testpres, testbackg, gm1)
ge2 <- evaluate(testpres, testbackg, gm2)
ge2
pg <- predict(predictors, gm2, ext=ext)
par(mfrow=c(1,2))
plot(pg, main='GLM/gaussian Current')
plot(wrld_simpl, add=TRUE, border='dark grey')
tr <- threshold(ge2, 'spec_sens')
tr
plot(pg > tr, main='presence/absence')
plot(wrld_simpl, add=TRUE, border='dark grey')
points(pres_train, pch= 21, cex=0.6, col='black')
points(backg_train, pch='-', cex=0.5)
```

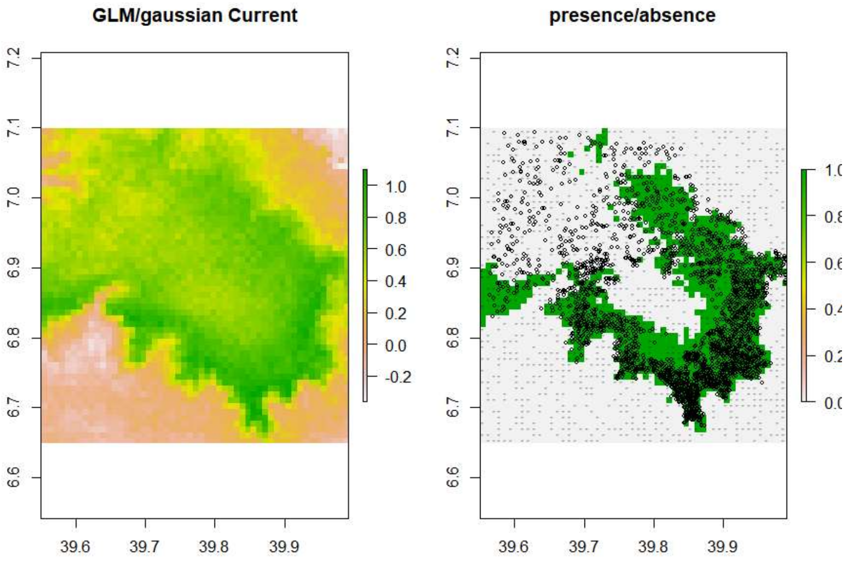


Figure 12: a) GLM/Gaussian current distribution range suitability scores map.
b) The prediction map that was subjectively classified into presence (green) /absence (gray) (threshold= 0.62)

d. Support Vector Machines

```
library(kernlab)
install.packages('kernlab')
svm <- ksvm(pa ~ bio1 + bio2 + bio3 + bio5 + bio8 + bio9 + bio11 + bio13 + bio14 + bio15 + bio18
+ bio19, data=envtrain)
esv <- evaluate(testpres, testbackg, svm)
esv
ps <- predict(predictors, svm, ext=ext)
par(mfrow=c(1,2))
plot(ps, main='SVM Current')
plot(wrld_simpl, add=TRUE, border='dark grey')
tr <- threshold(esv, 'spec_sens')
plot(ps > tr, main='presence/absence')
plot(wrld_simpl, add=TRUE, border='dark grey')
points(pres_train, pch= 21, cex=0.6, col='black')
points(backg_train, pch='-', cex=0.5)
```

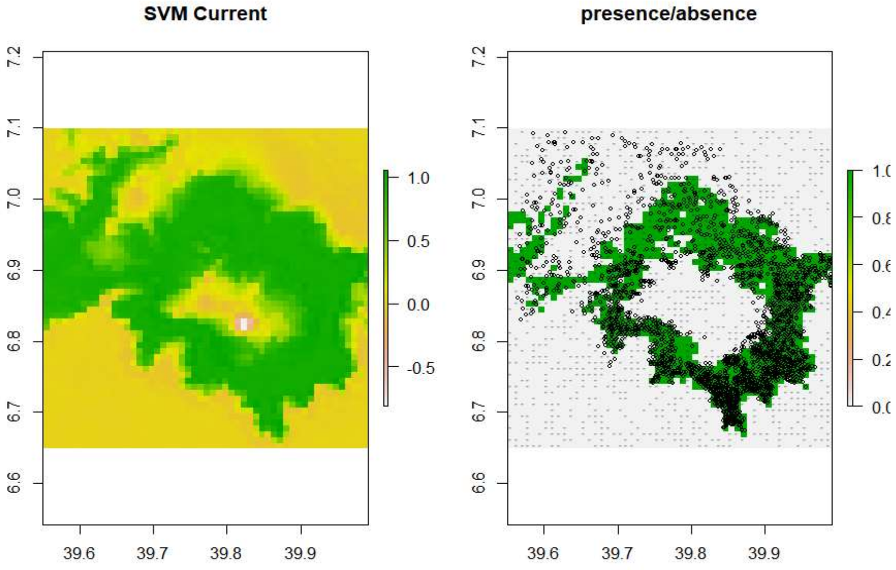


Figure 13: a) SVM current distribution range suitability scores map.
b) The prediction map that was subjectively classified into presence (green) /absence (gray) (threshold=0.63)

e. Combining model predictions

```
models <- stack(pb, pd, pg, ps)
names(models) <- c("Bioclim Current", "Domain Current", "GLM Current", "SVM Current")
plot(models)
m <- mean(models)
plot(m, main='Current average score')
auc <- sapply(list(e, ed, ge2, esv), function(x) x@auc)
w <- (auc-0.5)^2
m1 <- weighted.mean( models[[c("pb", "pd", "pg","ps")]], w)
plot(m1, main='weighted mean of four models')
```

11. Model average scores

```
# Weighed mean of all four current models average score
pa <- raster (m)
plot(m)
pa[]<- ifelse(m[] >= 0.3, 1, 0)
plot (pa, main='Weighted mean of Current')
```

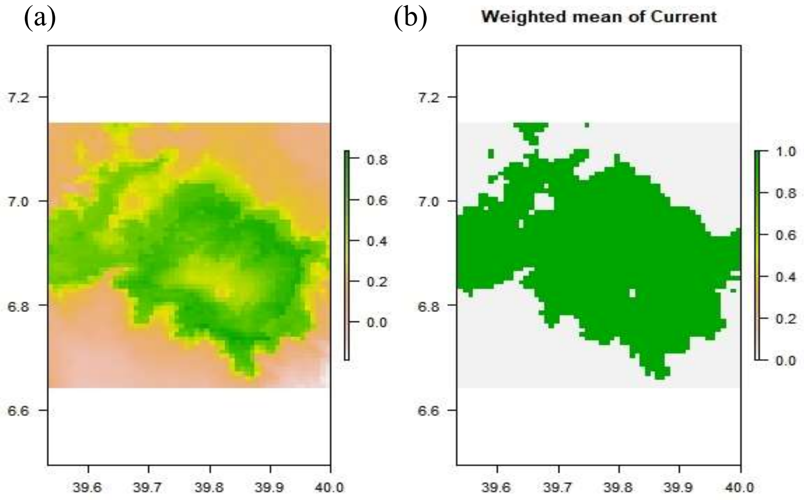


Figure 14: (a) The averaged suitability scores map of all four current models. (b) The averaged prediction map of all four models which was subjectively classified into presence (green) /absence (gray) (threshold = 0.51)

```
# Weighed mean current average score Future 50s
pafa <- raster (mfa)
plot(mfa)
pafa[]<- ifelse(mfa[] >= 0.3, 1, 0)
plot (pafa, main='weighted mean of 2050s')
```

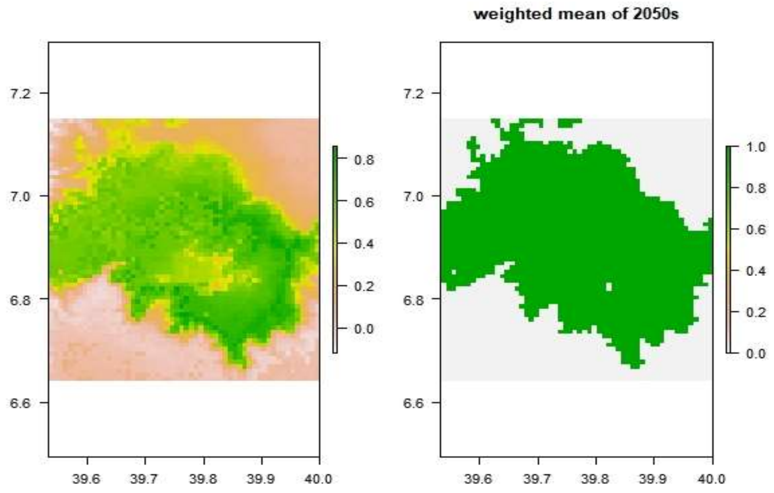

weighted mean of 2050s

Figure 15: (a) The averaged suitability scores map of all four 2050’s models. (b) The averaged prediction map of all four models which was subjectively classified into presence (green) /absence (gray) (threshold = 0.6)

```
# Weighed mean current average score future 70s raster (mfb)
plot(mfb)
pafb[]<- ifelse(mfb[] >= 0.3, 1, 0)
plot (pafb,main='Weighted mean of 2070s')
```

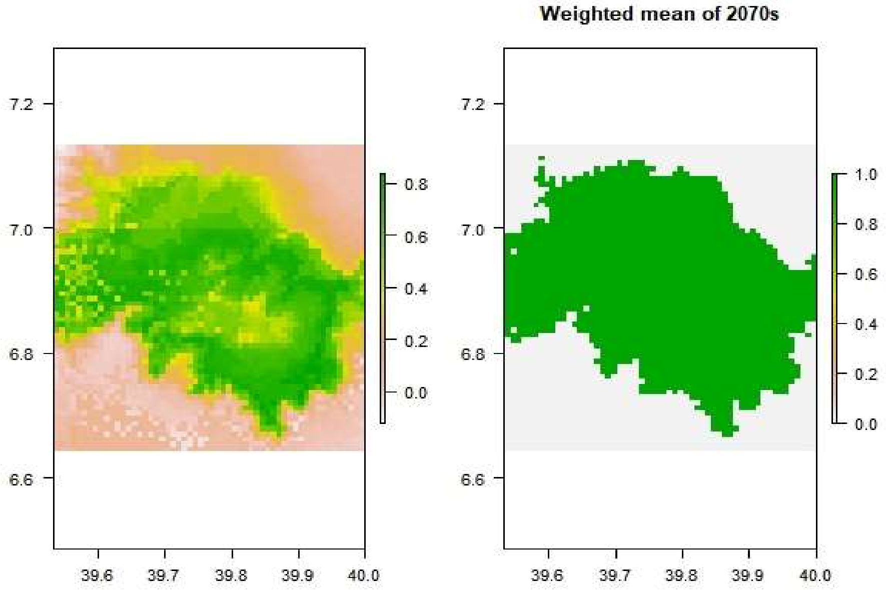
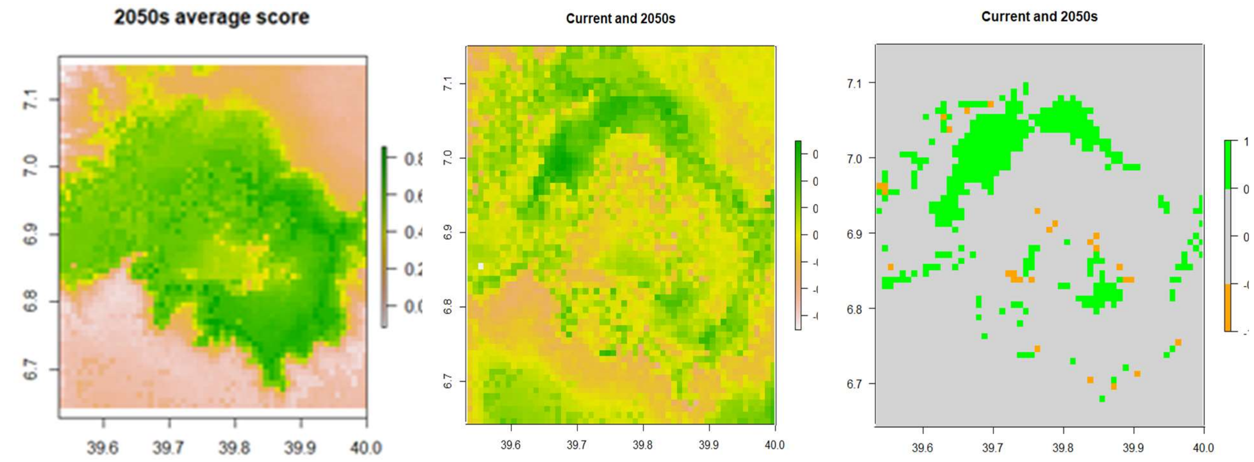

Weighted mean of 2070s

Figure 16: (a) The averaged suitability scores map of all four 2070’s models. (b) The averaged prediction map of all four models which was subjectively classified into presence (green) /absence (gray) (threshold = 0.61)

12. Calculating the difference between models (change Detection)

```
# difference between current and future 2050’s
plot(m, main='Current')
m
plot(mfa, main='2050s')
mfa
pac <- mfa-m
plot (pac, main='Current and 2050s')
pac
cl <- colorRampPalette(c('orange', 'lightgray', 'green'))
plot(pac, col=cl(3), main='Current and 2050s')
```

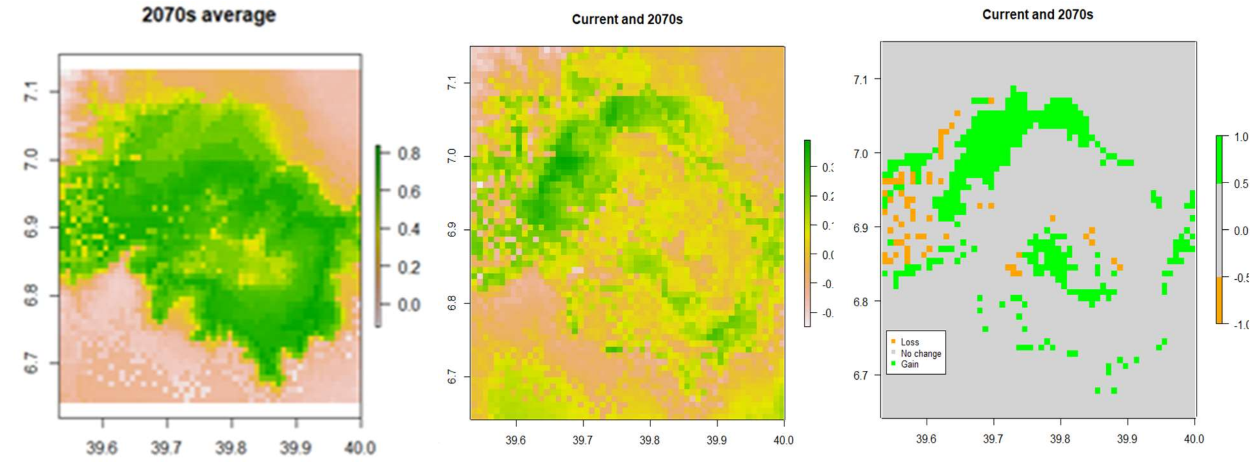

2050s average score

Current and 2050s

Current and 2050s

Figure 17: (a) The averaged suitability scores map of the difference between current and 2050's models. (b) The averaged suitability scores map of the difference between current and 2050's models which was subjectively classified into areas of gain (Green), loss (Orange) and no change (Gray).

```
# difference between current and future 2070’s
plot(m, main='Current')
m
plot(mfb, main='2070s')
mfb
pac <- mfb-m
plot (pac, main='Current and 2070s')
cl <- colorRampPalette(c('orange', 'lightgray', 'green'))
plot(pac, col=cl(3), main='Current and 2070s')
```


2070s average

Current and 2070s

Current and 2070s

Figure 18: (a) The averaged suitability scores map of the difference between current and 2070's models. (b) The averaged suitability scores map of the difference between current and 2070's models which was subjectively classified into areas of gain (Green), loss (Orange) and no change (Gray).

13. Reference

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., and Jarvis, A., 2005. Very high-resolution interpolated climate surfaces for global land areas. International Journal of Climatology. 25, 1965-1978.

Hijmans, R.J., van Etten, J., 2011. raster: Geographic Analysis and Modeling with Raster Data. R package version 1.8-39, URL http://CRAN.R-project.org/package=raster (accessed July 2020).

Hijmans, R.J., and Elith, J., 2017. Species distribution modeling with R. https://cran.r-project.org/web/packages/dismo/vignettes/sdm.pdf (accessed April 2021).

Naimi, B., and Araújo, M.B., 2016. SDM: a reproducible and extensible R platform for species distribution modeling. Ecography. 39, 368–375. DOI: 10.1111/ecog.01881.

Naimi, B., Hamm, N.A.S., Groen, T.A., Skidmore, A.K., and Toxopeus, A.G., 2014. Where is positional uncertainty a problem for species distribution modeling? Ecography. 37 (2), 191-203.

R Core Team. 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing [Internet]. http://www.R-project.org/.

Attachment II: Erica sampling data points

Nº	species	lat	lon	alt
1	Erica	6.712718	39.90395	3200
2	Erica	6.804442	39.95387	3200
3	Erica	6.762687	39.96884	3201
4	Erica	6.923988	39.97547	3202
5	Erica	6.816775	39.67908	3202
6	Erica	6.855978	39.96332	3202
7	Erica	6.814859	39.6754	3203
8	Erica	6.867394	39.66312	3203
9	Erica	6.982194	39.91281	3203
10	Erica	6.730306	39.8253	3204
11	Erica	6.830132	39.56829	3205
12	Erica	6.841292	39.58601	3205
13	Erica	6.883203	39.97051	3206
14	Erica	6.740665	39.94003	3206
15	Erica	6.711997	39.83326	3206
.				
.				
3219	Erica	6.800517	39.90305	3884
3220	Erica	6.793763	39.8877	3884

Table 1: The Erica occurrence points with latitude, longitude, and altitude of occurrence.

List of Publications

1. **Kidane, YO;** Stahlmann, R; Beierkuhnlein, C: Vegetation dynamics, and land use and land cover change in the Bale Mountains, Ethiopia., Environmental Monitoring & Assessment, 184, 7473–7489 (2012) doi:10.1007/s10661-011-2514-8

2. **Kidane, YO;** Steinbauer, MJ; Beierkuhnlein, C: Dead end for endemic plant species? A biodiversity hotspot under pressure, Global Ecology and Conservation, 19(e00670) (2019) doi:10.1016/j.gecco.2019.e00670

3. **Kidane, YO;** Hoffmann, S; Jaeschke, A; Beloiu, M; Beierkuhnlein, C: Ericaceous Vegetation of the Bale Mountains of Ethiopia Will Prevail in the Face of Climate Change., Scientific Reports, 1-24 (2022) doi:10.21203/rs.3.rs-620392/v1

4. **Kidane, YO** and Beierkuhnlein, C: Synergistic impacts of climate and land use land cover (LULC) change on vascular plants diversity and distribution along the Bale Mountains: *hotpot of afroalpine biodiversity. Review.* Frontiers in Ecology and Evolution. (2022) *(accepted under review).*

5. **Kidane, YO** and Beierkuhnlein, C: Biodiversity Across Afroalpine Environments and the Role of the Synergy Between Climate and Land Use Land Cover (LULC) Change. Communication. Peerj (submitted). (2022).

6. Steinbauer, MJ; Irl, S; González, JM; Breiner, F; Hernández Hernández, RM; Hopfenmüller, S; **Kidane, YO;** Jentsch, A; Beierkuhnlein, C: Plant invasion and speciation along elevational gradients on the oceanic island La Palma, Canary Islands, Ecology and Evolution, 7(2), 771-779 (2017) doi:10.1002/ece3.2640

7. Gallou, A., Jump, A., Lynn, J., Beierkuhnlein, C., Chen, J-C., Chou, C-H., Field, R., Hemp, A., Irl, S.D.H., **Kidane, YO.,** König, C., Kreft, K., Naqinezhad, A., Nowak, A.. Nuppenau, J-N, O'Sullivan, K., Price, J., Roland, C., Schweiger, A., Steinbauer, M., and P.Weigelt, P: Diurnal temperature variation drives elevational range sizes in vascular plants at a global scale. Science (*to be submitted*) (2022)

(Eidesstattliche) Versicherungen und Erklärungen

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