UNIVERSITY OF NAIROBI

BIOTIC EFFECTS OF CLIMATE CHANGE IN THE TROPICAL ALPINE MOORLANDS OF MOUNT KENYA AND MOUNT ELGON, AND ITS IMPACT ON DEPENDENT LOCAL COMMUNITIES

BY

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DECLARATION

I declare that this dissertation/thesis is my original work and has not been submitted elsewhere for examination, award of a degree or publication. Where other people's work or my own work has been used, this has properly been acknowledged and referenced in accordance with the University of Nairobi's requirements.

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To my Dad, the late Raymond Victor Downing

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ABSTRACT

Tropical alpine areas are extraordinary ecosystems that provide valuable services including water, biodiversity, and food. These areas are uniquely threatened by climate change as they are predicted to warm more over the next century than other areas of the globe, and may be more sensitive to that change as the biotic communities have narrow thermal niches. While the threat to climate change on tropical mountains is widely appreciated, there have been remarkably few studies documenting the impacts and effects on the wider socio-ecological system. This is particularly true in East Africa where these mountains support large vulnerable populations. This study examined the impacts of climate change in two alpine areas of Kenya - Mount Kenya and Mount Elgon. It examined patterns and trends in the climate, ecology, and socio-economic setting of these two mountains. Climate trends were investigated using reanalysis datasets, meteorological station data, and in-situ data loggers. Ecological trends were examined through a resurvey of a historical vegetation study from 1980 in the Teleki Valley of Mount Kenya. Socioeconomic patterns were explored through household questionnaires, focus group discussions, and key informant interviews. The data was analysed with descriptive statistics to demonstrate patterns and changes in those patterns. Results indicated that temperature has warmed consistently in the alpine zones of both mountains - warming at a rate of 0.2-0.3° C/decade. Precipitation has not changed appreciably up on the two mountains, but down by the base there have been changes in seasonal patterns and streamflow. Vegetation patterns have not changed much over the 40 year period, with most of the dominant species existing in similar densities and distributions as in 1980. The biggest changes were a decline in species diversity, and shifts in the distribution and demography of the characteristic *Dendrosenecion keniodendron* species. Communities surrounding the two mountains rely heavily on mountain ecosystem services for their livelihoods, and most particularly water provision. These communities have noticed changes in ecosystems service delivery over their lifetimes, but few considered climate change as the primary challenge they face. The afro-alpine socio-ecological systems of Kenya are changing in response to climate change, but there are also indications of resilience and inertia in these systems: the changes have not been as pronounced as expected. More ecological research and monitoring is needed to better understand these unique and important ecosystems in order to prepare for future changes. The possible existence of ecological tipping points present a particular concern.

Key Words: Tropical Alpine, Climate Change, Vegetation Shifts, Climate Trends and Variability, Ecosystem Services, Adaptive Capacity, Socio-Ecological System

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LIST OF ACRONYMS

ADF	- Augmented Dickey-Fuller Test
ASAL	- Arid and Semi-arid Lands
CCA	- Canonical Correspondence Analysis
CETRAD	- Centre for Training and Integrated Research in ASAL Development
CFSR	- Climate Forecast System Reanalysis
DJF	- December-January-February
ECMWF	- European Centre for Medium-Range Weather Forecasts
EDW	- Elevation Dependent Warming
ENSO	- El Nino Southern Oscillation
ERA5	- ECMWF Reanalysis v5
ES	- Ecosystem Services
GCM	- Global Circulation Models
IOD	- Indian Ocean Dipole
IPCC	- Intergovernmental Panel on Climate Change (IPCC)
ITCZ	- Inter-Tropical Convergence Zone
JJA	- June-July-August
KALRO	- Kenya Agriculture & livestock Research Organization
KPSS	- Kwiatkowski–Phillips–Schmidt–Shin Test
LGM	- Last Glacial Maximum
LOWESS	- Locally-Weighted Scatter Plot (LOWESS)
MAM	- March-April-May
NCP	- Nature's Contribution to People
NMDS	- Non-metric Multidimensional Scaling

NRM3	- Natural Resources Monitoring, Modeling and Management
PLR	- Power Law Range
SOM	- September-October-November
SST	- Sea Surface Temperatures
WRA	- Kenya Water Resources Authority

DEFINITION OF TERMS

Unless otherwise stated definitions are from Merriam-Webster Dictionary

(Merriam-Webster, 2023)

Acaulescent- having no stem or appearing to have none

Albedo- reflective power- specifically: the fraction of incident radiation (such as light) that is reflected by a surface or body (such as the moon or a cloud)

Alleopathy- the effect of a plant's metabolic products on the growth of nearby plants (Study Smarter UK, 2022)

Biogeography- a science that deals with the geographical distribution of animals and plants

Ecological niche- a habitat supplying the factors necessary for the existence of an organism or species; the ecological role of an organism in a community especially in regard to food consumption

Ecotype- a population of a species that survives as a distinct group through environmental selection and isolation and that is comparable with a taxonomic subspecies

Endemic- restricted or peculiar to a locality or region

Evapotranspiration- loss of water from the soil both by evaporation and by transpiration from the plants growing thereon

Facilitation- when one species benefits from the presence of another and neither are harmed (Study Smarter UK, 2022)

Iteroparity- life histories characterized by living to reproduce repeatedly (Young, 2010)

Lapse rate- the adiabatic rate of decrease of atmospheric temperature with increasing altitude

Likert- designed to measure people's attitudes, opinions, or perceptions. Subjects choose from a range of possible responses to a specific question or statement (Brittanica, 2023)

Morphology- the form and structure of an organism or any of its parts

Nival- characterized by, abounding with, or living in or under snow: of or relating to a region of perennial snow

Orography- a branch of physical geography that deals with mountains

Pedology- soil science

Phenotype- the observable characteristics or traits of an organism that are produced by the interaction of the genotype and the environment: the physical expression of one or more genes

Recruitment- the process of adding new individuals to a population or subpopulation (as of breeding or legally catchable individuals) by growth, reproduction, immigration, and stocking

Resilience- an ability to recover from or adjust easily to misfortune or change

Rosette- a cluster of leaves in crowded circles or spirals arising basally from a crown (as in the dandelion) or apically from an axis with greatly shortened internodes (as in many tropical palms)

Sclerophyllous- characterized by hard, leathery, evergreen foliage that is specially adapted to prevent moisture loss (Brittanica, 2023)

Semalparity- life histories characterized by death after first reproduction (Young, 2010)

Talus- a slope formed especially by an accumulation of rock debris; rock debris at the base of a cliff

Tussock- a compact tuft especially of grass or sedge

Xeric- characterized by, relating to, or requiring only a small amount of moisture

Chapter 1 INTRODUCTION

1.1. Background to the study

1.1.1 Global overview

1.1.1.1 Mountains

Mountains have an importance globally that belies their small geographic coverage. Even broadly defined, mountains only cover a quarter of the Earth's surface (Mountain Partnership, 2014), but they provide over half of the world's fresh water and account for over half of the global biodiversity hotspots (Kohler & Maselli, 2009). In arid zones, the contribution of mountains to the hydrological system is even more important, often contributing 90% of the total basin runoff; it is for this reason that mountains, particularly in arid and semi-arid regions, are referred to as 'Water Towers' (Messerli et al., 2004; Viviroli et al., 2007).

The topographic and altitiudinal gradients found in mountains affect world weather patterns and create for unique environments not found anywhere else (Viviroli et al., 2003). Global weather patterns are driven by solar radiation: evaporation from the oceans causes moist air to rise and moves outwards towards the poles. As the warm moist air moves over land, it may eventually encounter a mountain range. This forces the air to ascend in elevation, causing it to cool until it can no longer hold its moisture, at which point it releases the water as precipitation (Roe, 2005). Once the moisture falls, the mountain can store this water and regulate its release to the lower elevations. It does this through its micro-topography, vegetation, and soils. Mountains are characterized by complex topography which creates multiple depressions that act as sinks to store water (Buytaert et al., 2011). The mountain soils contribute to this, as they are generally rich in organic matter and thus have high water-holding capacity, infiltration capacity and hydraulic conductivity, such that most of the incoming rainfall gets captured into the soils, to then be released slowly throughout the year as subsurface lateral flow (Buytaert et al., 2006). The low temperatures in the upper mountains also means that evapo-transpiration is generally low, and so much of the incoming water is eventually released downstream (Célleri & Feyen, 2009). Therefore, runoff ratios in the mountains are high, while the peak flow to base flow ratios in the streams coming off the mountain are low (Buytaert et al., 2011).

The high biodiversity on mountains comes from the great diversity in habitats over short distances, caused by the extreme altitudinal gradients and complex micro-topography (Buytaert et al., 2011). These conditions create for very unique habitats found nowhere else, and thus the level of species endemism is particularly high on mountains (Myers et al., 2000). Unique environments lead to unique adaptations to very specific sets of conditions. This also makes mountains important genetic reserves for agro-biodiversity: some of these adaptations may become vital for addressing human food security in the future (Kohler & Maselli, 2009). Finally, the low temperatures found at the tops of the mountains create for situations of low microbial activity, allowing organic matter to accumulate. These carbon reserves can be a critical mitigation against climate change (Buytaert et al., 2011).

1.1.1.2 Tropical mountains

Tropical mountains have all the characteristics of other mountains, with some important differences. First of all, there is very little seasonal variation in mean temperature. Mean temperature throughout the year is relatively constant, though it changes markedly during the day. The thin atmosphere at the high elevation has a low heat capacity and therefore temperature can warm up and cool down very quickly above a certain altitude, it freezes every night and then thaws during the day (Hastenrath, 1991; Hedberg, 1964; Smith & Young, 1987). Precipitation patterns too have a seasonal element, driven by regional wind patterns, but even here the seasonality in the alpine zone is much less than in the lower elevations (Hedberg, 1964). Rainfall in tropical mountains reaches its peak at mid-elevations and then decreases again towards the top. This means that the alpine zone is both cold and dry, and with large temperate swings (Hedberg, 1964; Rundel et al., 1994). This daily freeze-thaw cycle creates for the existence of an important process of physical weathering of rocks that is not found anywhere else (Coe, 1967).

Tropical alpine areas occur in only a few countries around the globe, namely; Ecuador, Venezuela, Kenya, Tanzania, Ethiopia, Uganda, and New Guinea (Figure 1-1). The alpine area extends from the tree-line to the upper end of plant life, or from roughly 3,500 m.a.s.l to 5,000 m.a.s.l in elevation (Smith & Young, 1987). The unique climatic and topographic conditions in these areas have given rise to flora that are phenotypically quite similar despite the great distance separating them. This is thought to have occurred through a process of convergent evolution, as these floras have been forced to adapt to an incredibly specific envelope of climatic conditions (Buytaert et al., 2011; Smith & Young, 1987). The daily freeze/thaw cycle creates unique challenges for any biota living in that environment (Hedberg, 1964).

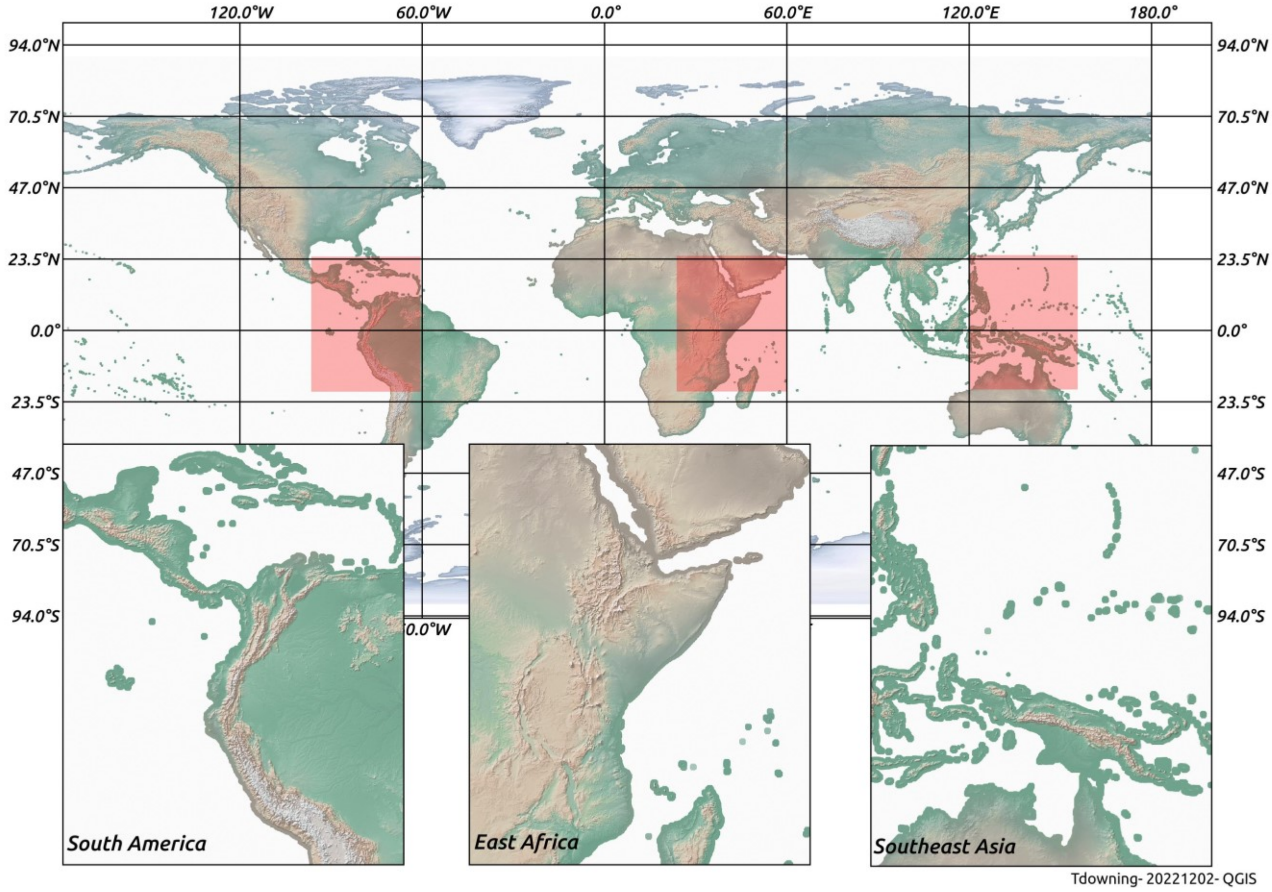

Figure 1-1 Tropical alpine areas of the world: hillshade map of the three regions of the world with alpine environments

1.1.1.3 Climate change in tropical mountains

Climate change is of concern in mountains all over the world. Given their disproportionate importance in the terrestrial environment, changes in these ecosystems have the potential to severely disrupt ecosystem services and threaten human livelihoods (Huber et al., 2005; Kohler & Maselli, 2009). The concern is that positive feedbacks can magnify changes on the mountains in ways that may still be unclear (Buytaert et al., 2011; Körner, 2005). Given the role of mountains in global weather and hydrology processes, small changes can have major impacts in the future (Kohler & Maselli, 2009). This concern is enhanced for tropical mountains given the large percentage of the population that lives near mountains and depend on them directly for their livelihoods, and these people are often among the most socio-economically vulnerable people - living in remote areas with poor access to resources (Capitani et al., 2019; Córdova et al., 2019; Hofer, 2005; Messerli et al., 2004). The alpine environments in the tropics are also ecologically very vulnerable as there is such a delicate balance between biotic and abiotic factors in these extreme environments (Hedberg, 1964; Sklenář et al., 2016; Smith & Young, 1987). Small changes in temperature will therefore likely have disproportionate impact on the ecology of these systems (Cuesta et al., 2020). This, in turn, will affect downstream ecosystem services (Buytaert et al., 2011). Finally, and most importantly, the magnitude of warming in tropical alpine environments is predicted to be higher than elsewhere; over the next century the warming in tropical alpine environments is expected to be some of the highest in the world (Anthelme et al., 2014).

1.1.2 Regional overview (East Africa)

The East African mountains (or Afro-alpine system) are an interesting subset of the tropical alpine environments, because they are generally not mountain ranges as the others are (Figure 1-2). Thus biogeographically they function as islands, leading some to term them 'sky islands' (Gehrke & Linder, 2009; Gizaw et al., 2016). The mountains are found on either side of the rift valley stretching from Ethiopia down to Tanzania (Mairal et al., 2017). They have different ages, origins, elevations, and geographical positions which creates for different climate and vegetation (Table 1-1). The driest mountains are the Ethiopian mountains (Gehrke & Linder, 2014), which also have the highest treelines (Jacob et al., 2015). Almost all of these mountains were glaciated in the Last Glacial Maximum (LGM) period, but currently only Mount Kilimanjaro, Kenya, and the Rwenzori mountains still have glaciers (Osmaston & Harrison, 2005).

The Afro-alpine 'sky islands' were likely colonized by flora during past periods of maximum glaciation, when there was habitat connectivity between the mountain and with temperate zones sharing a similar climate (Brochmann et al., 2022; Chala et al., 2017). The isolation of alpine flora, combined with their narrow ecological niche, suggests that these ecosystems will likely be especially vulnerable to the impacts of climate change (Brochmann et al., 2022; Chala et al., 2016). Genetic variability within afroalpine plant communities is very low due to frequent bottlenecks caused by past climate changes and lack of regular genetic material exchange. (Brochmann et al., 2022).

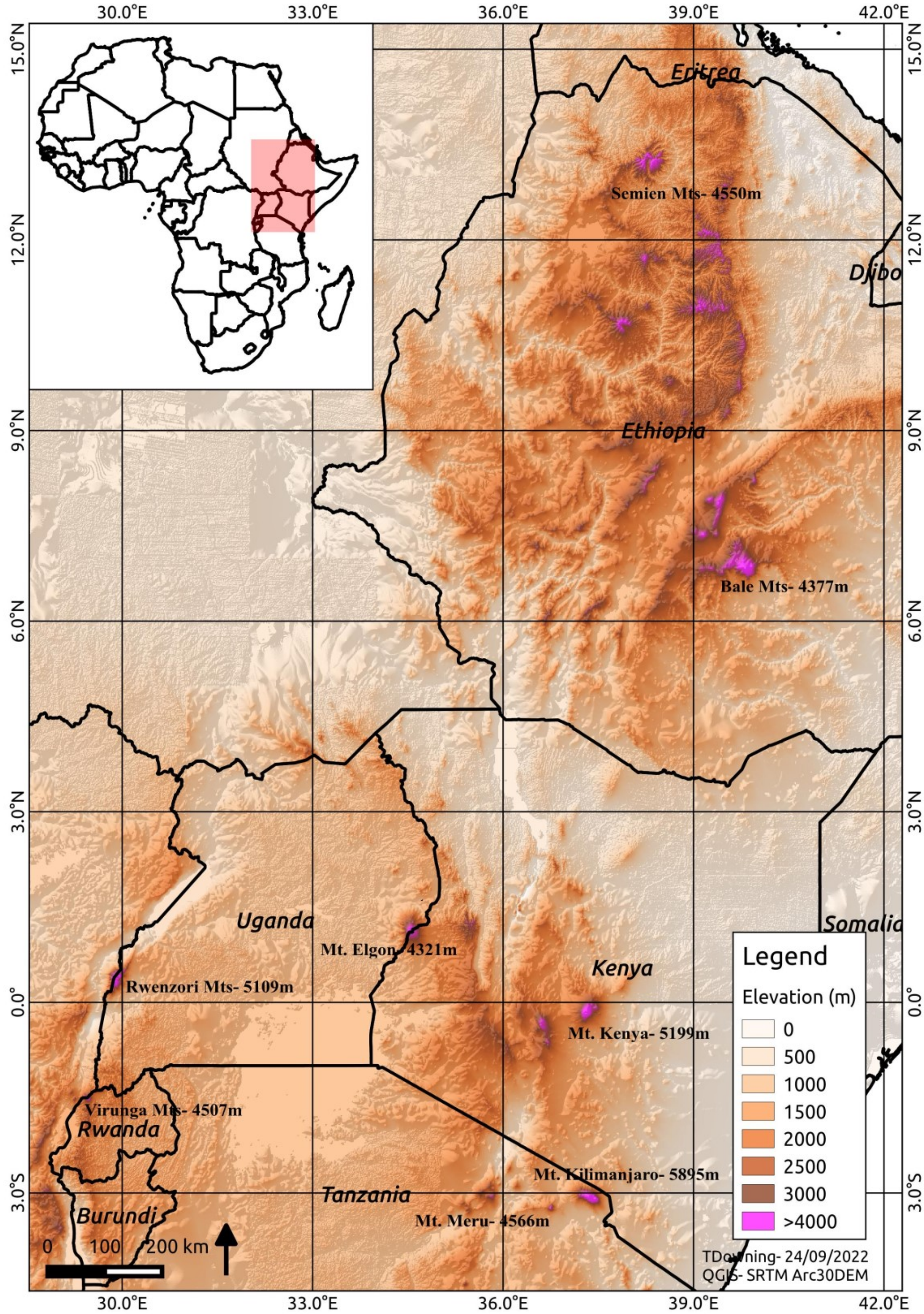

Figure 1-2 The Afro-alpine mountain system: elevation and hillshade of the East African highlands. Highest point elevations are given in meters above sea level

Table 1-1 Biophysical characteristics of the Afro-alpine mountain system

Mountain/ Range	Siemen Mts (Ras Dashen)	Bale Mts (Sanetti)	Rwenzori Mts (Mt. Stanley)	Virunga Mts (Karisimbi)	Mt. Elgon	Mt. Kenya	Mt. Kilimanjaro	Mt. Meru
Country	Ethiopia	Ethiopia	Uganda	Uganda/ Rwanda/ DR Congo	Uganda/ Kenya	Kenya	Tanzania	Tanzania
Lat/ Long	13.25/ 38.45	6.83/ 39.83	0.38/ 29.88	1.51/ 29.45	1.25/ 34.55	-0.16/ 37.33	-0.16/ 37.33	-0.16/ 37.33
Rift Valley Position^	Ethiopian Rift	Ethiopian Rift	Albertine Rift	Albertine Rift	Gregory Rift	Gregory Rift	Gregory Rift	Gregory Rift
Highest Point (m.a.s.l)*	4550	4377	5109	4507	4321	5199	5895	4566
Estimated Age (million years)*	>40	>40	3 - 8	8.9 - 12.6	12-23	2.5 - 5	1.9 - 2.5	1.5 - 2.0
Orogeny*	Volcanic/ Tectonic faulting	Volcanic	Crystallin e/ Tectonic faulting	Volcanic	Volcanic	Volcanic	Volcanic	Volcanic
Precipitation (mm)*	800-1500	850-1100	1500-3000	1500-2500	1000-1270	900-2500	1350-2000	1200-1800
Humid Side+	NE	S	W	E	n/a	E	SW	S
Area >3000m (km^2)++	1398	1980	587	n/a	662	708	622	n/a
Tree line elevation (m.a.s.l)#	4000	4000	3900	3800	3300	3400	3800	n/a
Last Glacial Maximum extent-km^2)**	13	600	260	Not glaciated at LGM	70	220	120	Not glaciated at LGM

(+Bussmann, 2006; Gehrke & Linder, 2014;++ Groos et al., 2021; #Jacob et al., 2015;^ Mairal et al., 2017; Maizlish, 2004; **Osmaston & Harrison, 2005)*

1.1.3 Study area overview

Among the East African mountains, two stand out as particularly interesting places to document impacts of climate change: Mount Kenya and Mount Elgon (Figure 1-3). These mountains are two of the most truly tropical in location, and are separated by <350 km, along an E-W transect, so they are subject to similar regional weather patterns (Hedberg, 1964). Yet the two mountains are also very unique, having different topography, geology, and land-use.

They are found on either side of the Rift Valley, meaning their floral genetic make-up is quite different, despite their proximity (Sklenář et al., 2014; Wondimu et al., 2014), and their geographic situation means that their climates are also distinct (Gehrke & Linder, 2014). Mount Elgon is significantly shorter, has no permanent ice, and is located more inland, whereas Mount Kenya is taller (5199 m.a.s.l vs. 4321 m.a.s.l), has 11 glaciers, and is closer to the coast and thus more influenced by coastal weather patterns. These factors can result in very different responses to the forces of climate change.

Socio-economically the two mountains are also different, with different ethnicities, livelihoods, and population densities. The two mountains have different land-use histories and fit into different socio-political settings. Mount Elgon is a trans-boundary ecosystem shared by Uganda and Kenya, whereas Mount Kenya is located completely within Kenya. Finally the different geographic situations means that orographic patterns are different for the two mountains, leading to different climates surrounding the mountains, and thus different landcover and land-uses (Bussmann, 2006b). Investigating impacts of climate change on

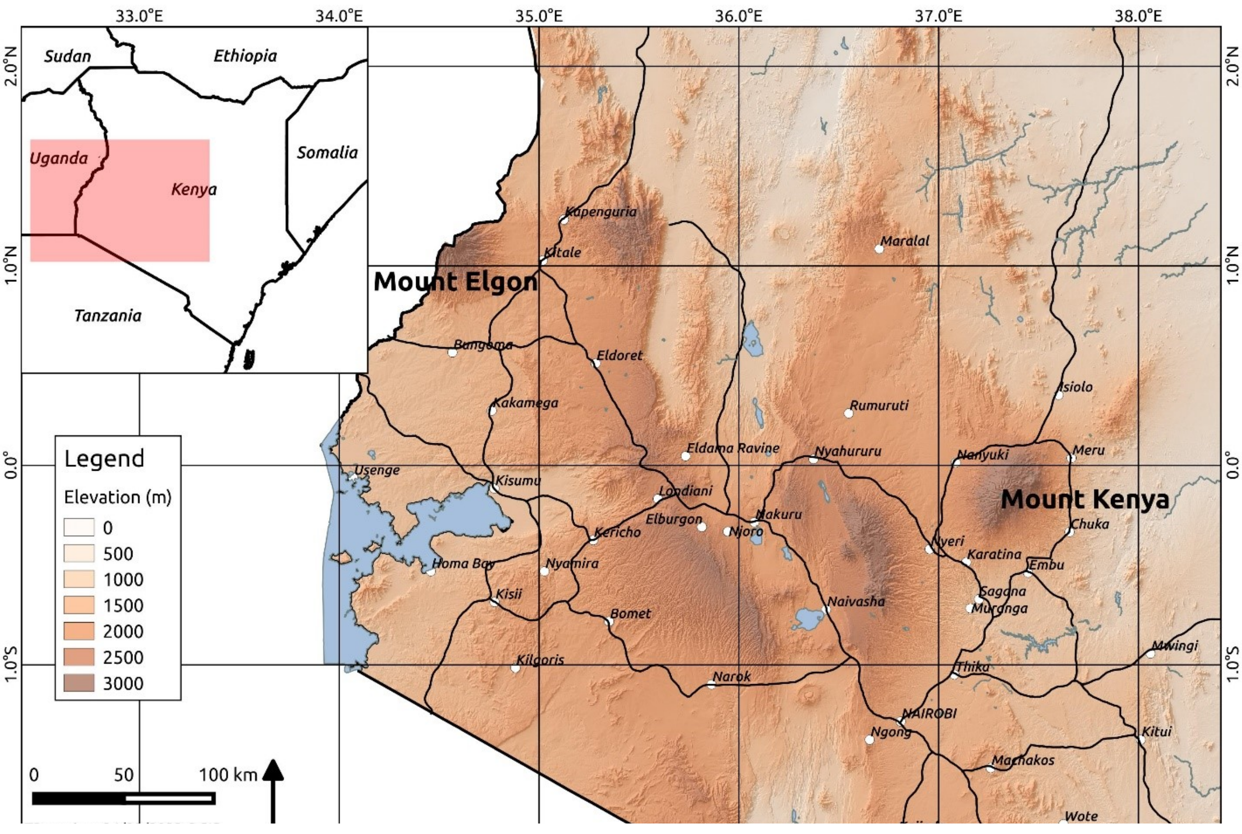

Figure 1-3 Location and topography of Mount Kenya and Mount Elgon in Kenya

these two mountains is thus a unique opportunity to investigate local socio-ecological vulnerability or resilience to climate change.

1.2 Statement of the problem

Tropical alpine areas are important ecosystems that provide valuable ecosystem services to surrounding communities; they are also exceptionally vulnerable to climate change (Buytaert et al., 2011; Grabherr et al., 2010; Huber et al., 2005). While the value of these ecosystems is well appreciated, there is much that is unknown about the ecology and sociology of these mountain systems, particularly in East Africa (Björnsen, 2005; Grabherr et al., 2010). Due to the remoteness of these mountains, there have been few long-term ecological or sociological studies of the alpine zone and human interactions with it. Many of the studies that exist are somewhat dated, but still provide valuable data into these important ecosystems (1980s (Beck et al., 1981, 1987; Hamilton & Perrott, 1981; Hedberg, 1957, 1964; Rehder et al., 1981; Speck, 1982; Young, 1990; Young & Peacock, 1985). There are also climatic data for the two mountains from at least the 1970s to the present (Ayugi et al., 2019; Camberlin et al., 2014; Henne et al., 2008; Konecky et al., 2014; Messmer et al., 2021). Socio-cultural investigations into community interactions with Kenyan highland ecosystems also exist and have begun to demonstrate the interconnectedness of some of these socio-ecological landscapes (Capitani et al., 2019; Chiyumba, 2015; Cuni-Sanchez, Omeny, et al., 2019; Nyamweru, 2012). However, what is missing from the current state of knowledge is a detailed understanding of how this socio-ecological landscape has been and is being impacted by climate change. There have been remarkably few studies actually documenting climate trends in these two mountains, few long-term vegetation monitoring studies, and few investigations of human interaction with the alpine zone in particular.

The research questions for this study are:

- What are the climatic patterns and trends on the two mountains and how have these changed over the last half century?
- What are the vegetation and soil patterns on the two mountains and how have these changed over the last half century?
- What ecosystem services do local communities recognize in alpine areas and what changes have been observed in these areas over the last half century?

1.3 Objective of the study

1.3.1 Main objective

The overall objective of this study was to document the bio-climatic dynamics of the alpine zones of Mount Kenya and Mount Elgon, the interactions between local communities and the alpine resources, and the implications for community adaptation to climate change

1.3.2 Specific objectives

The specific objectives were:

1) To determine temperature, precipitation, and streamflow trends on the two mountains over the past half century;
2) To characterize the vegetation patterns in the Teleki valley of Mount Kenya and analyse changes over the past 40 years;
3) To investigate how local communities perceive and utilize the alpine zones and what changes they have observed over the years.

1.4 Scope and limitations of the study

1.4.1 Scope

Studying the impacts of climate change across both mountains in their entirety was clearly not feasible for such a study, so a representative valley in each mountain was used as a specific study area, and socio-economic impacts were limited to the areas downstream of these valleys. These are the Teleki and Koitobos valleys of Mount Kenya and Mount Elgon, respectively (Figure 1-4). In this way, fine-scale patterns with respect to temperature, soils, and flora could be investigated in-situ, as well as broader-scale sociologic and climatic patterns. The two valleys are characteristic of each mountain, with similar climate, soils, geology, and vegetation as the other radial valleys extending outwards from the peaks. These two valleys have been studied well in the past as they contain popular hiking routes up the mountains - the Naro Moru trail for Mount Kenya, and the Koitobos trail for Mount Elgon. For the broader scale socio-cultural investigation, communities immediately downstream from the two study area valleys, in the Bungoma and Nyeri counties were targeted as the study population. A 20 km radius was used as rough estimate of the area likely to directly influence and be influenced by changes in the alpine zone. Bungoma and Nyeri cover different topographic aspects of their respective mountainas, so they do not represent the same orographic conditions - Bungoma overall represents a moister aspect than Nyeri. This means the comparison between the two is not exact, but neither is it very far off.

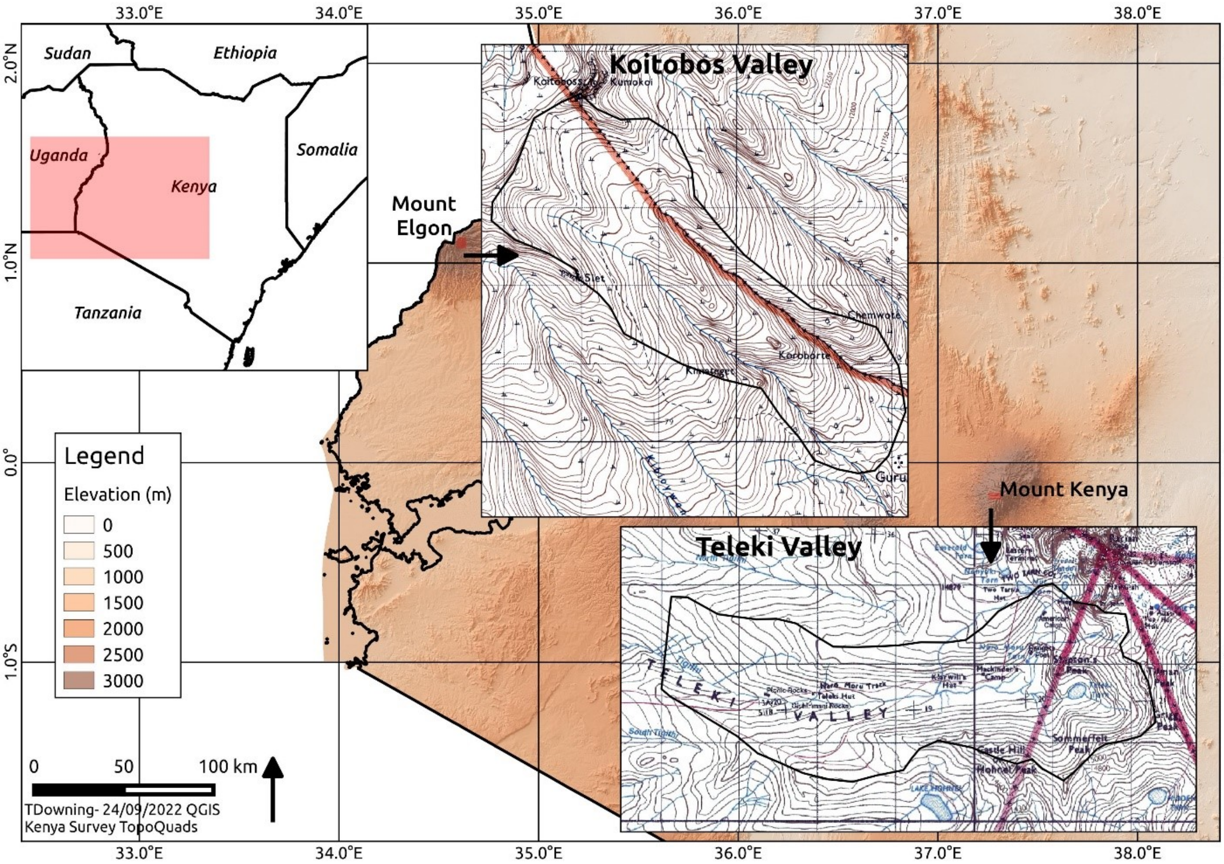

Figure 1-4 Specific study areas of the Teleki and Koitobos valleys in Mount Kenya and Mount Elgon

1.4.2 Limitations

This study was limited by scope and data availability. The scope of this study was necessarily restricted due to time and finance constraints, so the conclusions of this study are tentative. Given the complex socio-cultural environment surrounding the mountains, there is a high degree of variability across time and space. The current study provides just a snapshot of the situation, but more studies will be needed to see how well these results hold up over time and in different areas. In addition, attribution of change is confounded by so many factors above and beyond climate change. Land-use change, anthropogenic fire, and the socio-political situation all influence the biotic and abiotic environment in ways that are hard to separate. Data availability and quality was another limitation. Climate data was limited in these remote areas and the data that did exist was sometimes of uncertain quality. Vegetation data was limited by technical and access constraints. The original study serving as the baseline dataset (Young & Peacock, 1992) was conducted before the days of GPS which made revisiting the exact sample sites impossible. Budgetary constraints further meant that a full inventory was not possible: grasses could not be confidently identified in their mostly non-reproductive state at the time of the study. Socio-economic data was constrained by the level of engagement of the respondents.

The transdisciplinary framework employed in this research depends on constant iteration in a feedback loop: asking questions, testing questions, and reformulating questions. Obviously this whole arc cannot be completed in one study, so the hope is that the results from this study can be reformulated and investigated further based on the recommendations and study questions that emerge from this thesis. It is for this reason that the recommendations for further study in this thesis are quite extensive.

1.5 Structure of the thesis

Chapter 1 of this thesis introduces the topic and outlines the objectives of study. Chapter 2 is a literature review that highlights the recent knowledge and gaps in the three subject areas of climate, vegetation, and human dimensions in the Afro-alpine areas of Kenya. Chapter 3 then introduces the study area in depth, and the bio-physical and socio-economic aspects of the two mountains. Next the specific methodology is presented for each objective - outlining the data sources used, and the analysis tools used to extract information from those data sources. The results from the three objectives are then reported in the next three chapters (Chapters 4-6). These chapters present the climatic, ecological, and socio-economic patterns and trends for the two mountains, as well as a discussion engaging in relevant recent literature. Chapter 7 then provides a synthesis of the three sets of results, to pull out overarching patterns in themes in a transdiciplinary framework. Finally Chapter 8 summarizes the findings in a set of conclusions and recommendations for future study. The implications for policy and land management is also explored.

Chapter 2 LITERATURE REVIEW

2.1 Introduction

Vulnerability to climate change can be expressed as a function of exposure, sensitivity, and adaptive capacity (Adger, 2006). The first two terms have both a biophysical and socio-economic dimension (Füssel, 2007). By either standard, tropical alpine areas emerge as some of the most vulnerable areas to climate change in the world (Buytaert et al., 2006; Messerli et al., 2004). Different emission scenarios from Global Circulation Models (GCMs) indicate that tropical alpine areas are expected to warm more than other areas of the world. In fact, the warming may be over twice as great - a warming of 4° C over the next century as compared to a global average warming of 1.5° to 2° C (Bradley et al., 2006; Büchler et al., 2004; Diaz et al., 2014; Urrutia & Vuille, 2009). Tropical alpine ecology is also very sensitive to these changes. The hydrology, pedology and biodiversity of the area all rely on a very narrow envelope of climate variability (Cuesta et al., 2020; Hedberg, 1964; Sklenář et al., 2014). Socio-economically, tropical alpine areas are again both exposed and sensitive: mountain communities directly rely on mountain resources more than many other communities around the globe, and they are generally poorer and more marginalized (Capitani et al., 2019; Córdova et al., 2019; Rolando et al., 2017). Adaptive capacity then refers to the ability of the system to cope with these changes (Adger, 2006). Essentially this is the resilience of the system and again this can be thought of biophysically and socio-economically (Gallopín, 2006).

There has been considerable speculation on the impacts of climate change on tropical alpine areas, but the studies are short on specifics. There is general agreement that climate change will impact biodiversity, carbon and water cycles, but how much is under debate (Buytaert et al., 2011; Grabherr et al., 2010; Kohler & Maselli, 2009). The IPCC AR6 report identifies mountain regions around the world as particularly vulnerable to climate impacts, and suggests that in some cases these areas have already reached limits of natural adaptation, which can lead to irreversible changes. It further states with high confidence that the changes observed in these regions are directly attributable climate change. Societies living around these mountainous areas are typically already stressed, and climate change will further increase their vulnerability. But the report also notes that in the short term there will be both positive and negative impacts (IPCC, 2022b).

The IPCC also conducted a special report on cryosphere responses to climate change, with a chapter specifically dedicated to high mountain regions (IPCC, 2022a). A summary of these changes are listed in Table 2-1. The observed changes have largely been negative/adverse, although there have been some positive changes. With respect to low-latitude mountains, the report concludes that water availability has both increased and decreased (high confidence), and that moorland and riverine ecosystems have been both positively and negatively affected (low confidence). On the other hand, agriculture and cultural services have been negatively affected (low/medium confidence), and there has been an overall increase in net migration (low confidence) (IPCC, 2022c).

Looking specifically at the categories in this thesis - temperature, precipitation, vegetation, and ecosystem services - the report has the following predictions for high mountain areas in general (IPCC, 2022c, 2022a):

- Temperature has been increasing by an average of 0.3° C/decade in the high mountain areas and is projected to continue at 0.3° C/decade (high confidence)
- Precipitation has not had any trend so far (medium confidence), except for snowfall decreases attributable to the increasing temperatures (high confidence). Future projections suggest increases of 5-20% over the next century for various mountains including those in eastern Africa
- Streamflow has both increased and decreased - depending on the mountain - and the timing has changed (very high confidence). Future projections suggest more of the same, but for tropical mountains the indication is mostly of declining yields - that runoff will decrease by >10% by 2100 particularly in the dry season (low confidence)
- Vegetation has been increasing in high elevation areas with increasing species richness higher up due to upslope movements (very high confidence). However, there have also been declines of certain cold-adapted species (high confidence). Future projections suggest continued upslope movements and shrinking of ranges (high confidence) as well as extinctions of certain mountain top species (medium confidence)
- Ecosystem services have been both positively and negatively affected, particularly with respect to water availability. But future projections suggest declines in tourism

and cultural resources (high confidence), as well as declines in regulating services, such as soil stability, causing increases in mountain hazards such as floods and landslides (high confidence).

There are other auxiliary changes predicted with varying degrees of confidence, such as further reduction in glaciers and snow cover, thawing of permafrost, and increasing wildfire frequency and intensity, which are correlated with the physical changes noted above. Generally the models predict more of the same changes already observed, but with time many of the positive effects go away. The temporary increases in streamflow and vegetation cover change to declines, as glaciers are exhausted and as species begin to die off from heat exposure.

Table 2-1 Observed and predicted changes in the high mountain areas of the world, with associated confidence, according to IPCC report

	Observed Changes		***Predicted changes***
A.1.1	Glacier reduction (very high confidence)	B.1.1	Further glacial reductions by more than 80% by 2100 (medium confidence)
A.1.2	Decline in snow cover (high confidence)	B.1.3	Decreases in snow depth of 10- 40% by 2050 (high confidence)
A.1.3	Decrease stability of mountain slopes due to ice thaw (high confidence)	B.1.4	Continued permafrost thaw (very high confidence) releasing extra carbon into the atmosphere (medium confidence)
A.4.1	Increases in species in mountains due to upslope shifting (very high confidence), but also declines (extinctions) of cold adapted species on summits (high confidence)	B.4.1	Continued upslope migration of species, as well as shrinking ranges, and mortality of alpine species (high confidence), and overall species extinctions (medium confidence)
A.4.2	Increases in disturbances- particularly wildfire and hydrology related (high confidence)	B.4.3	Further changes to disturbances regimes with impacts on ecosystems (medium confidence), particularly increases wildfire intensity and frequency (medium confidence)
A.4.3	Temporary increases in plant productivity (medium confidence)	B.1.5	Decrease in slope stability and increase in glacier lake area (high confidence), leading to increased risk of floods and landslides (high confidence)
A.7.5	Increase in natural disasters (medium confidence)	B.7.1	Increase in hazards- flood, fires, landslides (high confidence), human exposure and vulnerability to these increase (high confidence)
A.7.6	Changes in amount and timing of runoff and streamflow (very high confidence), both increases and decreases in water quantity for example in Andes (medium confidence)	B.1.6	Changes in mountain runoff (very high confidence), for tropical mountains the already low level of glaciers means overall runoff will decrease by >10% by 2100 in the dry season (low confidence)
A.7.7	Loss of aesthetics, recreation, and tourism due to glacier and snow decline (medium confidence)	B.7.3	Declines in mountain tourism and cultural resources (high confidence)

(IPCC, 2022c)

The impacts of climate change, specifically in tropical alpine regions of the world, has probably been best reviewed by Buytaert et al. (2011). The authors examine the potential impact of climate change on tropical alpine ecosystem services. They find that most ecosystems services will be negatively affected, in particular biodiversity, carbon storage, and water supply. However they note that climate change effects will be very variable over space and time and that there is still much uncertainty as to specific effects. They note that the scarcity of data in these regions, and in particular long-term monitoring data, prevents the development of robust models in these remote environments (Buytaert et al., 2011).

A compilation of research on global change in mountain regions (Huber et al., 2005) summarizes these changes in terms of paleoenvironmental, cryospheric, hydrological, ecological, and human dimensions. The first three deal with changes in mountain climate and specifically temperature, precipitation, and stream flow regimes. Ecological impacts deals with changes to biodiversity and soil function, and the human dimension examines how these changes impact ecosystem services for communities living near the mountains.

2.2 Tropical alpine climate

2.2.1 Climate regimes of the afro-alpine ecosystems

Tropical-alpine climates are largely driven by elevation and latitude (Hedberg, 1964). Their location in the tropics means they are influenced by the tropical wind patterns of the Inter-Tropical Convergence Zone (ITCZ), which drives the regional climate (Hedberg, 1964). How these patterns are expressed on the mountains, however, depends on elevation. Temperature decreases by about 0.6° C per 100 m elevation gain, and this lapse rate is quite consistent across the afro-alpine region (Loomis et al., 2017; Rundel, 1994). This is a remarkably steep temperature gradient, and it means that within the space of a few kilometres there can be a completely different temperature regime - and therefore different ecological zone. Upon entering the alpine zone (>3500 m[3]) the minimum temperature is low enough to cause freezing (Hedberg, 1964), and by the end of the alpine zone (>5000 m), the mean temperature also is below zero (Hastenrath, 1991). Nonetheless, these mountains are still located in the tropics, so they receive a high dose of radiation. Being near the equator, the sun angle does

[3] m.a.s.l- hereafter just referred to as m unless otherwise indicated

not change much during the year, so this high radiation is received year-round. Also given the high altitude, the air pressure is very low (60% of the value at sea level), so it does less to block incoming radiation (Hedberg, 1964). This means that the temperature during the day can heat up remarkably fast. Warming in the morning can be as rapid as 10° C in half an hour (Hedberg, 1964; Young & Robe, 1986). The low pressure also means that the air has a low heat capacity, so it does not take long for the air to lose its heat at night. This sets up a condition for what Olov Hedberg terms 'summer every day, winter every night' (Hedberg, 1964). Each night it can go below freezing, while during the day the temperature can increase to above 25 °C (Beck et al., 1981; Wesche et al., 2000). Seasonal variation, on the other hand, is very minimal: the average seasonal variation in mean temperatures is only around 1.7 °C, whereas average daily swing is 8.9 °C (Coe, 1967). This freeze-thaw cycle on a daily basis then has profound impacts on soil processes, which experience a high level of physical weathering (Coe, 1967). For plants, the implication is that water can be unavailable much of the time, and plants have had to develop xeric adaptations despite being in areas that may receive plenty of moisture (Hedberg, 1964; Smith & Young, 1987).

There is nonetheless a high degree of spatial variability in temperatures on these mountains, which can be modified by topography, vegetation, and wind (Sklenář et al., 2016; Young & Robe, 1986). Winds moving along the ground can create for large temperature swings at the surface; during the day as the air warms, this warm air flows upslope, while at night it flows downslope (Hedberg, 1964). This means that temperature changes along a vertical profile as well, with temperature swings highest on the surface and then decreasing with height off the ground (Hedbergs & Hedberg, 1979; Young & Robe, 1986). It is why many plants grow tall at these elevations to escape the drastic temperature swings at the surface (Chala et al., 2016). Vegetation and rock talus, on the other hand, can buffer these temperature swings, creating for thermal micro-niches separated even just by a few hundred meters (Beck et al., 1981; Hedberg, 1964; Mora et al., 2019). These factors create for a wide variety of temperatures over short distances, and there is an overall similarity in tropical alpine temperatures around the world (Table 2-2). Temperature varies most by elevation - due to the lapse rate - but also by vertical depth/height, vegetation and topographic conditions. There are, however, few (if any) long term detailed records to fully capture the temperature regime in these areas (see Table 2-2).

Temperatures, in turn, influence precipitation patterns. In East Africa, the regional precipitation patterns are dictated by the Indian Ocean Sea Surface Temperatures (SST) which drive the air movements (Camberlin et al., 2014). Generally speaking, there are two rainy seasons: a long rainy season from March-May and a short rainy season from September-November. The long rains are the heaviest and most consistent, while the short rains are much more variable (Messmer et al., 2021). In a normal year (i.e. one without El Niño Southern Oscillation (ENSO) or Indian Ocean Dipole (IOD) phenomena), the moisture bearing air masses for the long rains come from the south – the southern Indian Ocean - whereas for the short rains they come directly from the east (Konecky et al., 2014). As these air masses come in from the ocean, they encounter the mountains and are forced upward, causing them to cool and eventually release their moisture as rain.

Table 2-2 In-situ temperature measurements in tropical alpine areas around the world+

AUTHOR	**LOCATION**	**ELEVATION/ (SITE DETAIL)**	**HEIGHT**	**Min** (°C)	**Max** (°C)
Grab et al., 2004	Mt. Kenya (Kenya)	4200 m	-10cm	1.9	19.3
			-1cm	-7.7	40.7
			surface	-7.2	42.8
Bader et al., 2007	Andes Mts. (Ecuador)	3600 m (forest)	-3cm	3.7	12.6
			15cm	2.5	15.2
			150cm	2	13.7
		3600 m (grass moorland)	-3cm	6.6	14.1
			15cm	-2.4	31.9
			150cm	2	19
Beck et al., 1981	Mt. Kenya (Kenya)	4030 m (valley bottom)	-2cm	-4	15
			surface	-6	16
		4066 m (valley sides)	-2cm	-3	20
			surface	-5	18
Sklenar et al., 2016	Andes Mts. (Ecuador)	4120 m (east aspect)	-10cm	3.5	6.2
			-1cm	1.1	16.6
			20cm	-3.3	16.3
		4280 m (west aspect)	-10cm	3.2	12.6
			-1cm	-0.5	30.8
			20cm	-6.6	23
Wesche, 2002	Mt. Elgon (Kenya/Uganda)	3750 m	20cm	-6	25.8
			200cm	-4	18.5
Wesche et al., 2000	Bale Mts. (Ethiopia)	4030 m (*Erica* shrubland)	-50cm	4.3*	n/a
		4030 m (*Erica* nearby)	-50cm	9.0*	n/a
		4020 m (No *Erica* nearby)	-50cm	7.7*	n/a
Gutlein et al., 2017	Mt. Kilimanjaro (Tanzania)	3880 m (low vegetation)	-2cm	6.4*	n/a
			-10cm	6.2*	n/a
		3800 m (shrub vegetation)	-2cm	5.9*	n/a
			-10cm	5.8*	n/a
Mora et al., 2018	Andes Mts. (Venezuela)	~4300 m near rosette East facing	surface	1.2	10.8
		~4300 m near rosette West facing	surface	0.7	16.7
		~4300 m away from rosette	surface	-0.2	21.7

*Mean temperatures
+(Bader et al., 2007; Beck et al., 1981; Grab et al., 2004; Gütlein et al., 2017; Mora et al., 2019; Sklenář et al., 2016; Wesche, 2002; Wesche et al., 2000)

Elevation then affects these air masses in somewhat predictable ways. As temperature decreases with elevation, there comes a point where the clouds can no longer hold their moisture and so release it. This generally happens mid-way up the mountain at elevations of around ~3,000 m (Coe, 1967). This effect is consistent enough that the duration, onset, and cessation dates of the rainy seasons are fairly predictable according to elevation and aspect (Camberlin et al., 2014). The alpine zone, however, is above these regional wind currents, and in general is less affected by these wind patterns (Hedberg, 1964). By this point, the air masses have largely already dropped their moisture, so precipitation is less, and in fact the tops of the mountain can be very dry (Coe, 1967). Thus the predictable seasonality of the lower slopes disappears by the alpine zone, and rainfall can occur at any time. Rainfall is driven more by topography, creating local atmospheric instabilities, than by any regional pattern, and this causes highly variable rain patterns over short distances (Bacchi & Villi, 2005). Generally speaking, however, rainfall is more common in the afternoons due to the daily convection patterns, and that is when the stratum of clouds forms around the mountain peaks. This pattern is driven by surface wind movements: the warmer air from lower elevations rises up the slope to the higher elevations where it cools and forms clouds in the afternoon; at night the reverse process occurs (Hedberg, 1964).

These climatic conditions in turn drive the hydrological regime on the tropical mountains. The low temperatures, high cloud cover, and low water use by plants, means that in general evapotranspiration is low. Therefore, the runoff ratio is very high, and given the consistency of rainfall throughout the year (even if the total is small), the mountains produce a lot of water (Buytaert et al., 2011). Topographic depressions and wetlands create water sinks that store overflow water, and the peat soils - with their high water storage potential - can slowly release water throughout the year. This creates for conditions were the peak flow to baseflow ratio for tropical alpine areas is unusually low (Buytaert et al., 2011). This steady source of water is particularly important in dry lowlands, where it may be the biggest contribution to rivers even far downstream (Hagg & Braun, 2005). Around Mount Kenya, streamflow varies by season, but is slightly out-of-phase with precipitation, and there is generally a baseflow throughout the year (Leibundgut, 1983).

2.2.2 Elevation dependent warming

Climate models suggest that warming in tropical alpine regions will be higher than in the surrounding lowlands over the next century (Anthelme et al., 2014; Bradley et al., 2006; Chala et al., 2016). This is due to a phenomenon known as Elevation Dependent Warming (EDW) (Mountain Research Initiative, 2015). The result of increasing warming at higher elevations is that the lapse rate is predicted to decrease under climate change (Loomis et al., 2017; Urrutia & Vuille, 2009). While the exact mechanisms are not fully understood, this EDW is caused in part by feedbacks that become more important as one increases in elevation; these include albedo, clouds and water vapour, radiative fluxes, and aerosols (Liu et al., 2009; Mountain Research Initiative, 2015; Rangwala & Miller, 2012). Albedo positive feedbacks have been noted before in the Poles, where an increase in temperature causes more snow to melt, which causes less heat to be radiated away and thus further warming (Thackeray & Fletcher, 2016). Feedbacks regarding clouds occur when enhanced warming causes an increase in evaporation and thus water vapour and cloud formation. Particularly at night, these clouds serve to trap heat and radiate it back to earth. These processes occur more at high elevations, where diurnal temperature changes bring about a daily cycle in cloud formation. This process suggest that night-time minimum temperature would be expected to increase faster than maximum temperatures in these high elevations (Duan & Wu, 2006; Mountain Research Initiative, 2015; Rangwala & Miller, 2012). As to why low latitude areas would be particularly susceptible to warming, this is thought to have something to do with El Niño Southern Oscillation (ENSO) which generally serve to moderate temperatures in the tropics (Diaz et al., 2014). As these cycles become destabilized, the moderating effect on temperatures might be lost.

There are other feedback mechanisms that are still not well understood pertaining to water vapour, aerosols, and soil moisture which can have conflicting responses to warming temperatures, and it is for this reason that there is uncertainty in the magnitude of warming in alpine areas (Mountain Research Initiative, 2015). EDW has been demonstrated in empirical data particularly from reanalysis datasets (Bradley et al., 2009; Diaz et al., 2003, 2014; Seidel & Free, 2003), but evidence from ground station data is a little more inconclusive with some evidence to the contrary (Lu et al., 2010; Pepin & Lundquist, 2008; Vuille, 2013; Vuille & Bradley, 2000). For tropical alpine areas in particular, ground station data is sparse and often the stations that do exist are poorly sited or poorly maintained (Mountain Research Initiative, 2015). The largest data set comes from the Andes where there are 279 ground stations from different elevations with data going back to 1930: these have demonstrated an overall increase in temperatures in the Andes of about 0.1° C/decade, but not necessarily a greater warming at higher elevations (Vuille et al., 2003, 2008).

2.2.3 Changes to the hydrological cycle

The impact of alpine warming on regional precipitation and hydrology patterns is similarly difficult to predict (Buytaert et al., 2011). Globally, the IPCC predicts with medium confidence that climate changes will lead to more variability in precipitation - with heavier precipitation in certain areas and increases in the frequency of drought in others. In high elevation areas the models generally suggest increases in precipitation, but there is less confidence in these estimates (IPCC, 2018).

The most visible sign of climate change in the tropical mountains is in the glaciers, which have experienced marked declines over the past half century (Chen et al., 2018; Kaser et al., 2005; Prinz et al., 2018; Taylor et al., 2006; Veettil & Kamp, 2019). Multiple factors are involved in glacier reduction, however, so glacier melting in some cases has more to do with changes in precipitation and solar radiation than in temperature increases (Kaser et al., 2005; Prinz et al., 2018). Whatever the exact cause, the loss of glaciers has profound impacts on the hydrology of the mountain systems (Huss et al., 2017). Melting of glaciers has led to great increases in discharge in certain parts of the world and particularly spikes in seasonal high flows (Barry, 2005). These hydrological extremes will likely be amplified as warming temperatures continues to alter the bio-physical characteristics of the mountain - reducing soil organic matter and increasing evapotranspiration (Buytaert et al., 2006). A loss of soil organic matter will reduce the water storage capacity of the mountains, and increased evapotranspiration will reduce the runoff ratios. The net result is expected to be an increase the peakflow to baseflow ratios downstream (Buytaert et al., 2011; Huss et al., 2017). In Kenya, this decline in baseflow has been documented, although it is difficult to separate out how much of this is due to climate change and how much is just due to increases in water abstraction (Leibundgut, 1983; Liniger et al., 2005).

While the impacts of climate warming on streamflow are somewhat predictable, the impacts on precipitation patterns are not very straight-forward. This is due to complicated interactions between topography, wind, soil moisture, and land cover that operate at different scales:

> *"It is important to note that in alpine catchments, meteorological, hydrological and glaciological phenomena undergo complex and highly variable interactions over short spatial and temporal scales. However, effects can be perpetuated over long distances and time."* (Bacchi & Villi, 2005).

And indeed, while warming trends have been consistently documented over the past century in tropical alpine areas, precipitation trends are less coherent: an analysis of a large dataset containing almost 100 years of data in the Andes showed no consistent trend: certain stations displayed increases in precipitation, others decreases, and others no trends at all (Vuille et al., 2003). In Kenya too, precipitation trends have been mixed. No clear trends in total precipitation amounts, have emerged, although there are signs of increasing variability (Ayugi et al., 2016; Ongoma et al., 2016; Schmocker et al., 2016). Around Mount Kenya, precipitation during the long rains decreased from 1979-2011, but increased for the short rains (Schmocker et al., 2016). The inter annual variability of the short rains (September-November) in particular has increased, and this is attributed to increased variability in the Indian ocean temperatures, as the short rains come from the east while the long rains come from the south (Konecky et al., 2014; Messmer et al., 2021). Other aspects of precipitation are more a function of local factors, aspect and exposure, and thus there are less clear trends when it comes to climate change (Camberlin et al., 2014).

2.3 Tropical alpine ecology

2.3.1 Afro-alpine plant communities

2.3.1.1 Species richness

The afro-alpine zone is known for its relatively low species diversity, but high percentage of endemic species. A survey of alpine flora of the East African mountains found 371 species in 141 genera, with most genera having just one species (Sklenář et al., 2014). If the sub-alpine zone is also included, this increases to 521 species in 191 genera (Gehrke & Linder, 2014). Mount Elgon has the highest species richness of all the East Africa mountains (273 species), and the highest number of endemics for a single mountain (5%). Mount Kenya is not far behind, with 269 species and 2% endemics (Gehrke & Linder, 2014).

There is clearly a lot of dispersal between the different afro-alpine peaks, and many studies have attempted to answer the question of how the peaks were initially colonized, and how much exchange of genetic information occurs (Assefa et al., 2007; Chala et al., 2017; Gehrke & Linder, 2009; Gizaw et al., 2013; Wondimu et al., 2014). During the last period of maximum glaciation, for example, the treeline was 1,000 m lower than it is today and thus the alpine habitat of East Africa was some 8 times larger (Chala et al., 2016, 2017). This would have enabled connection between many of the current 'islands' particularly in Ethiopia. It is thought that most alpine species came from Eurasian relatives that spread into Africa during each glacial period (Brochmann et al., 2022). However, genetic dissimilarity between the populations east of the Rift Valley with those west of the Rift Valley suggests that even during colder periods, the valley may have acted as a barrier to migration, being too low to accommodate alpine species (Brochmann et al., 2022; Wondimu et al., 2014). There is also evidence of more recent colonization - either from lowland areas or from island to island - by birds or wind (Assefa et al., 2007). As predicted by island biogeography, the Ethiopian mountains, which are the largest and oldest of the East African mountains, have the most species and endemism (Gehrke & Linder, 2014), while Mount Meru in Tanzania, the youngest and smallest, has the least (Sklenář et al., 2014). Mountains that are closer together share more species, and the closer they are the more they share. Mount Elgon and Mount Kenya are separated by 329 km and share some 170 species (Sklenář et al., 2014 - supplementary material).

Of the true afro-alpine flora species, the number that are vascular plants ranges between 70 and 150 species depending on the mountain (Hedberg, 1957). The majority of that diversity can be found in any given valley of the mountain, although naturally this varies according to aspect. In the two valleys investigated in this study - Teleki and Koitobos - different surveys have recorded varying figures - likely a function of the sampling intensity (Table 2-3).

Table 2-3 Species richness from select surveys in Teleki and Koitobos Valleys, Mount Kenya

AUTHOR*	**Elevation range (# of samples)**	**No. of Vascular Plant Species**
Teleki Valley		
Hedberg, 1964	4100m - 4200m (9 quadrats)	26
Rehder et al., 1981	3960m- 4480m (15plots)	42
Young and Peacock, 1992	3870m -4540m (45 transects)	61
Onipchenko et al., 2019	4170m – 4140m (10 nested plots)	28
Nekesa, 2015	3800m-4600m (elevation transect)	13
Koitobos Valley		
Hedberg, 1964	3600m-4100m (10 quadrats)	27
Beck et al., 1987	3764m-4145m (19 plots)	43
Wesche, 2002	3750m-4140m (IIH2- 13 samples)	57

**(Beck et al., 1987; Hedberg, 1964; Nekesa, 2015; Onipchenko et al., 2020; Rehder et al., 1981; Wesche, 2002; Young & Peacock, 1992)*

2.3.1.2 Plant associations

The most extensive accounting of Afro-alpine flora, even up to this day, comes from the Swedish scientist Olov Hedberg, who catalogued and analysed features of the African alpine ecosystems in the 1940s and 1950s. Hedberg investigated all the major tropical alpine ecosystems in East Africa: Mount Elgon, Mount Kenya, and the Aberdares in Kenya; Mount Kilimanjaro and Mount Meru in Tanzania; the Virunga Mountains in Rwanda/Democratic Republic of Congo; and the Ruwenzori Mountains in Uganda. His detailed descriptions of the vegetation in each of these mountain systems remains an invaluable source of baseline data. Much of his field work was conducted as part of the Swedish East Africa expedition of 1948 (Hedberg, 1957, 1964). Hedberg identified 5 principal communities common to all the afro-alpine areas. These were: *Dendrosenecio* woodlands, *Helichrysum* scrub, *Alchemilla* scrub, Tussock grasslands, and *Carex* bogs. These vegetation types were largely determined by valley position and elevation (see Appendix A2).

Later, in the early 1980s, two German scientists - E. Beck and H. Rehder - put forward a new classification scheme for the two mountains (Beck et al., 1987; Rehder et al., 1981, 1988) which sought to expand on the five community types of Hedberg and including subtypes. For Mount Elgon, 7 types were differentiated, which basically corresponded to the Hedberg types except that *Carex* bog and *Dendrosenecio* woodlands were expanded into 2 types each -

broken down according to edaphic conditions (moisture and soil drainage). In addition, the *Alchemilla* scrub was altered to include a *Euryops elgonensis* scrub, as the authors could not find any examples of pure *Alchemilla* scrub in Mount Elgon (Beck et al., 1987). For Mount Kenya, the Hedberg types were modified substantially. The biggest difference was to break down *Dendrosenecio* Woodlands into several communities based on composition, with varying ratios of *Dendrosenecios, Lobelias,* and *Erica* shrubs. The *Alchemilla, Helichrysum*, and Tussock grassland communities were reduced to just two communities - collectively called Upper Tussocks and Dwarf Shrubs - and a new class was created for the rock dominated habitats with scattered vegetation (Table 2-4). The reason for combining the scrub communities with the grasslands by the authors, is that they felt they were just different expressions of the same landscape. Due to the regular occurrence of fire, they envisioned the ecosystem oscillating between grass and shrub states (Rehder et al., 1981, 1988).

Table 2-4 Mount Kenya plant communities according to Rehder et al. 1988

Zone	**Code**	**Plant Community**
Upper wetland	F	Philippia-Dendrosenecio keniensis
	G	Philippia-Dendrosenecio keniodendron
	K	Dendrosenecio keniensis- Lobelia keniensis
	L	Dendrosenecio keniensis- Lobelia telekii
	N	Carex-Bog
Dendrosenecio woodland	M	Dendrosenecio keniensis- D. Keniodendron
	O	Lobelia telekii-Dendrosenecio keniodendron
Upper tussocks and dwarf shrubs	P	Festuca pilgeri-Alchemilla argyrophylla
	R	Open Lobelia telekii
Scattered vegetation	S	Senecio keniophytum

These plant community types are useful, but they remain somewhat subjective groupings (Young & Peacock, 1992). Nonetheless, the characterization of indicator species from these plant associations is useful. Rehder et al. (1988) identified 8 'main differentials' (indicators) which drove the plant communities in the upper alpine zone. These were: *Dendrosenecio keniensis, Dendrosenecio keniodendron, Lobelia keniensis, Lobelia telekii, Philippia keniensis/Erica arborea, Alchemilla argyrophylla, Festuca pilgeri,* and *Carex monostrachya*.

To this, the authors identified 'accessory differentials' as well as 'indifferents' which may or may not be present but did not determine the overall plant community. Interestingly, the authors did not include *Helichrysum* as an indicator species, even though Hedberg had considered it as one of the 5 main vegetation types.

2.3.1.3 Afro-alpine plant forms

The afro-alpine vascular plant species can also be grouped into five types based on growth form. These are the giant rosette, the tussock grass, the acaulescent rosette, the cushion plant, and the sclerophyllous shrub (Hedberg, 1964). Interestingly, the same growth forms can be found in all tropical alpine areas of the world (Hedbergs & Hedberg, 1979). The most distinctive growth form is the giant rosette, consisting of the Senecios and the Lobelias. These have a thick stem, which may be branched or unbranched, and are covered at the end by a dense mantel of leaves arranged in a rosette pattern. The outer leaves, which often are dead, protect the inner apical meristem as it grows (Hedberg, 1964). The next growth form, according to Hedberg, is the tussock grass, which occur in groups (tussocks) of both live and dead leaf blades. The major tussock grasses include: *Festuca piligeri, Poa schimperiana, Deschampsia flexuosa, Anthoxanthum nivale, Pentaschistis minor, Calamagrostis hedbergii,* and *Agrostis gracilifolia*. As with the rosette, this growth form serves to protect the growing plant tissue on the inside from climatic extremes. Acaulescent rosettes are leaf rosette plants without a stem: the leaves lie essentially flat against the ground, but have a large root system. These species prefer moist environments and include: *Conyza subscaposa, Nannoseris schimperi, Carduus platyphyllus, Haplocsciadium abyssinicum, Haplocarpha reupelli,* and *Ranunculus oreophytus*. Sometimes these plants grow to form continuous 'cushions' along the ground, but there just a few species that can truly be called 'cushion plants': *Agrostis sclerophylla, Sagina afroalpina, Swertia subnivals,* and *Myostis keniensis*. Again these species prefer moist environments. Finally Hedberg distinguishes the sclerophyllous shrubs which are dominated by the genera of *Erica, Alchemilla* and *Helichrysum*. These are woody shrubs that range from 10 cm tall to over several meters and are adapted to dry climates (Hedberg, 1964).

2.3.1.4 Giant rosettes

The Giant rosettes are the most striking feature of alpine landscapes. Early explorers commented on these unique plants (which they termed Giant Groundsels with their tree-like form inhabiting the very limits of plant life (Arthur, 1921; Gregory, 1896; Mackinder, 1900). They have a set of morphological adaptations to deal with these harsh conditions, which include: 1) growing very tall to escape cold temperatures at the ground; 2) having leaves (alive and dead) surrounding the apical meristem which fold inwards during the nights to insulate it from extreme temperatures; and 3) storing water within the plant to buffer thermal shocks (Chala et al., 2016).

Throughout the East African alpine range, there are a number of *Dendrosenecio* species that have distinct growth forms depending on habitat (Tusiime et al., 2020; Hedberg, 1964; Knox, 2005). In both Mount Elgon and Mount Kenya there are two primary species which are separated largely by elevation as well as edaphic conditions. In Mount Elgon, the two species are *D. barbatipes* and *D. elgonensis*, separated by an elevation of around 3900 m, while in Mount Kenya they are *D. keniodendron* and *D. keniensis* separated by an elevation of 4000 m. In both cases the lower elevation species is also more associated with flat, moist ground, whereas the latter is associated with slopes and well drained soils (Hedberg, 1964). There is very little genetic diversity among the *Dendrosenecios* in the East African mountains, and in fact the two species in Elgon have recently been classified as two subspecies of the same species: *D. elgonensis* (Knox, 2005). Mount Kenya is the only place where two different eco-types have evolved into two distinct species due to reproductive isolation despite living so close together (Tusiime et al., 2020). The two species have clear niche differentiation - *D. keniensis* is dominant in the valley bottoms and lower elevations while *D. keniodendron* dominates in the upper slopes and ridges. The two are also morphologically are quite distinct: *D. keniensis* is a short, prostrate plant, branching only close to the ground, whereas *D. keniodenron* is a tall erect plant (can grow up to 7m) and branches high off the ground (Tusiime et al., 2020). The Mount Elgon species (or subspecies), however, have similar growth forms. The main difference is that *D. elgonensis* doesn't branch as much as *D. barbatipes* (Beck et al., 1987).

The *Lobelia* genus are another giant rosette taxa, with similar niches as the *Dendrosenecios*. *Lobelia keniensis* often grows with *D. keniensis*, while *L.telekii* grows with D. *barbatipes* and

D. keniodendron (Hedberg, 1964). Table 2-5 shows their elevation ranges in Mount Kenya and Mount Elgon according to Hedberg (1957) who reported the ranges from the literature as well as the ranges that he had personally verified on both mountains. Elevations ranges from a more recent survey show that they haven't changed much, although if anything the upper end of the range has reduced (Knox, 2005). The elevation ranges also indicate a large amount of overlap on each mountain between the species, even though they inhabit very different ecological niches.

Table 2-5 Giant rosette species elevation ranges in Kenya

Species	**Location**	**Range as compiled by Hedberg, 1957 ()- Range personally verified**	**Range according to Knox, 2005***
Lobelias			
Lobelia keniensis	Mt. Kenya	3050m(3450)-4350m	n/a
Lobelia elgonensis	Mt. Elgon	3700m-4100m	n/a
Lobelia telekii	Mt. Kenya	3050m(3850)-4550m	n/a
Lobelia telekii	Mt. Elgon	3350m(3550)-4300m	n/a
Senecios			
Senecio keniensis	Mt. Kenya	3300m-4500m	3300m- 4275m
Senecio elgonensis	Mt. Elgon	3200m-4250m	2750m- 4200m
Senecio barbatipes	Mt. Elgon	3650m-4300m	3750m- 4225m
Senecio keniodendron	Mt. Kenya	3500m(3800)-4650m	3650m- 4350m

**As recorded in Tusiime et al., 2020*

2.3.2 Species range shifts

Alpine flora will most likely respond to climate warming by either adapting, migrating, or facing local extinction (Buytaert et al., 2011). Typically, the assumption is that species will shift up in elevation in response to the increasing temperatures (Bässler et al., 2013; Buytaert et al., 2011; IPCC, 2022b; Konvicka et al., 2003; Moritz et al., 2008; Walther et al., 2005). Warmer temperatures can open up previously inhabitable areas to plant colonization, whereas other species with cool climate life history requirements are forced to shift upwards for survival (Bodin et al., 2013; Coals et al., 2018; Crimmins et al., 2011; Lenoir et al., 2010; O'Sullivan et al., 2021).

Globally, upward shifts in elevation have been documented in small mammals (Moritz et al., 2008), butterflies (Konvicka et al., 2003), birds (Bässler et al., 2013), amphibians (Seimon et al., 2017), and alpine vegetation (Hope, 2014; Jurasinski & Kreyling, 2007; Walther et al., 2005). Within the Afro-alpine ecosystems also, vegetation shifts have been documented. In the Simien Mountains of Ethiopia an upward shift of 120 m was documented in *Erica* spp. between 1970 to 2000 (Wesche et al., 2000). Even in Mount Kenya, upwards shifts of 50-70 m have been documented in some of the Giant Senecios and Lobelias, although this was in response to a receding glacier (Mizuno, 2005). Overall elevation shifts have been on the order of 50 to 200 m increase in elevation over the last century (Bässler et al., 2013), and current temperature projections suggest that tropical alpine species may need to continue moving upward by 140- 800 m in order to maintain ecological viability (Buytaert et al., 2011). Several recent papers have suggested that downward migration may also be a response to climate change, as species shift in response to soil moisture or other ecological factors rather than temperature alone. Downward shifts have been observed in vegetation in mountains all over the world (Bodin et al., 2013; Coals et al., 2018; Crimmins et al., 2011; Dolezal et al., 2016; O'Sullivan et al., 2021). In many cases downward shifts were observed alongside upwards shifts, suggesting multiple responses to climate change (Bodin et al., 2013; Dolezal et al., 2016; O'Sullivan et al., 2021).

The upward or downward migration of species also depends on other factors beyond just the abiotic environment - these factors include competition, facilitation, human disturbance, and fire. A study on the Ericaceous belt of several of the East African mountains found that fire seemed to be the biggest driver of change for the treeline ecotone, outweighing the direct impacts of climate change (Wesche et al., 2000). It appears that there are feedback loops that serve to keep the treeline in its present location despite warming temperatures (Jacob et al., 2015). Often the soil temperature above the treeline is actually warmer than below, due to the micro-habitat created by the forest cover (Bader et al., 2007; Wesche et al., 2000). The presence of other species can also modify how certain plants respond to a warming climate. Warming reduces cold stress, enhances nutrient availability, and thus leads to greater growth and more inter- and intra-specific competition. On the other hand, environments higher up on the mountain are characterized by higher abiotic stress, and plants often survive in these areas only through facilitation: early colonizers facilitate later arrivals through habitat modification (Anthelme et al., 2014). The interaction between competition and facilitation can further complicate the responses to climate change - facilitation can expand a species' realized niche, while competition reduces it (Hupp, 2016). These forces can create entirely new plant community assemblages, as different species respond differently to their new abiotic and biotic surroundings (Körner, 2005).

2.3.3 Species adaptation or extinction

The species that are not able to shift in response to changing climate will be forced to adapt or face local extinction (Buytaert et al., 2011; Isaac & Williams, 2007). Adaptation in place is indeed possible, and perhaps more common than is sometimes realized. Some recent studies have noted the remarkable stability of Arctic vegetation communities despite rapid climate changes (Callaghan et al., 2022; Cirtwill et al., 2022). Furthermore, in the complex terrain of mountain environments there is the possibility of thermal refugia allowing species to survive despite rapidly changing conditions outside (Ackerly et al., 2020; Buytaert et al., 2011). This topographic diversity can also allow pockets of genetic diversity to survive, allowing for greater phenotypic plasticity (De Kort et al., 2020). Finally, the CO_2 'fertilizer effect', whereby increase in CO_2 in the environment can enhance plant productivity, is a very real factor particularly in higher elevations where carbon is limiting due to the low partial pressures of CO_2. This fertilization effect may counteract the detrimental effects of warming for certain species (Körner, 2005; Shugart, 2005).

If a species fails to shift or adapt, however, local extinction is a possibility. Indeed the giant rosettes in tropical alpine areas may be particularly vulnerable to extinction given their large size, long life span, slow growth and low rates of reproduction (Isaac & Williams, 2007). Climate change extinctions have already occurred and are expected to accelerate in the coming decades (Franco et al., 2006; Urban, 2015). The danger, particularly for isolated alpine mountains, is that as plants move up in elevation, the total habitat area decreases. Total area shrinks exponentially with each upward shift, and it soon may become too small to support a viable population. For example, models of *Lobelia rhynchopetalum* habitat in Ethiopia show that a 400 m shift upwards in elevation corresponds to an 80-90% loss of habitat, and an 82% loss in genetic diversity (Chala et al., 2016). These dispersal barriers - so called 'climatic traps'- create situations where extinctions become very likely (Lenoir & Svenning, 2015).

2.4 Tropical alpine socio-cultural setting

2.4.1 Afro alpine ecosystem services

Tropical Alpine areas are utilized to varying degrees around the world (Ashenafi et al., 2012; Buytaert et al., 2006; Hope, 2014). The South American alpine zone, known locally as the *Paramos*, is the largest and probably has the highest level of human use (Célleri & Feyen, 2009; Poulenard et al., 2001; Sarmiento et al., 2003). Archaeological evidence shows that *Paramos* have been used for hunting and gathering for centuries, and historical records provide evidence of agriculture and livestock grazing as well (Chepstow-Lusty et al., 1996; López-Zent, 1993). Ethiopian highlands have similarly been utilized by local peoples for centuries, mostly for livestock grazing and resource extraction. Even today there are communal rules and regulations for use of these areas, which include grass cutting, grazing, and firewood collection (Ashenafi et al., 2012). Most alpine areas, tropical or otherwise, tend not to be used directly by people but rather are appreciated for the suite of environmental and economic benefits that are derived from them. These have been termed Ecosystem Services (Adhikari et al., 2018; MEA, 2005) or Nature's Contribution to People (Christie et al., 2019; Pascual et al., 2017).

In general four types of Ecosystem Services are recognized: provisioning, regulating, cultural, and support services (MEA, 2005). The indirect services - regulating, cultural, and support - from alpine areas include natural disaster reduction (landslide/floods), climate regulation, biodiversity support, and cultural heritage. These types of services and have been recognized in mountain areas of the world including East Africa (Capitani et al., 2019), Pakistan (Bhatta et al., 2019), and Nepal (Adhikari et al., 2018). Some of these services come from the mountains as a whole, whereas some are unique to the alpine zone itself (ACCESS/IUCN, 2014).

For many communities the importance of the alpine area itself is mostly cultural. Tropical alpine areas are known throughout the world as places of cultural and religious significance - even sacred value (Ramakrishnan, 2005). In South America, powerful medicines were known to exist in the *Paramos* which also had religious significance. These plants were collected from the very highest elevations in ceremonies at certain times of the year, and were known for their metaphysical healing powers (López-Zent, 1993). In Africa, mountains were often seen as manifestations of God and thus places of incredible importance (Mbiti, 1991). The very name of Mount Kenya points to the view of the mountain as holy. The word 'Kenya' is said to comes from the Kikuyu 'Kere-nyaga' (Kirinyaga) meaning the 'mountain of brightness' or 'place of wonder', because that is where God was said to have resided (Arthur, 1921). In fact, the early European explorers often had difficulty in finding guides willing to take them up the mountains, suggesting that interaction with the higher reaches of the mountains was limited, and perhaps even off-limits (Gregory, 1896; Mackinder, 1900). That being said, the Scottish explorer Mackinder records encountering some '*Wandorobo'* people (hunter-gatherers) up in the moorland at a height above 12,000 ft. (3657 m). Mackinder was surprised to find people at such a high elevation, but apparently was not able to question them as they ran off quickly (Mackinder, 1900).

2.4.2 Local observations of climate change

Most societies are aware of the threat of climate change in their environment. In a study on the highlands of East Africa, almost all respondents believed that under a climate 'business as usual' scenario, ecosystem services would be severely curtailed (Capitani et al., 2019). Some mountain communities have reported significant changes even within their lifetime, which they attribute to climate change. These include changes in temperature and precipitation patterns, natural disaster intensity and frequency, range and cropland productivity, and changes in species distribution and composition (Adhikari et al., 2018; Bhatta et al., 2019). They have even been able to document local species extinctions and the presence of novel species (Bhatta et al., 2019).

The importance of local observations of climate change has become increasingly recognized (Reyes-García et al., 2019; Savo et al., 2016). This is because local communities are more in tune to their surroundings and more likely to notice changes that occur in the ecosystem services that they rely on (Cuni-Sanchez, Omeny, et al., 2019). Local observations can serve to validate climate models and they provide a level of detail that is currently lacking in model outputs. And indeed there has been good agreement between local observations and model predictions across the globe. For some parts of the world, particularly remote areas, local observations are all that exist (Reyes-García et al., 2019). This is partly the case for the mountains of East Africa, where permanent meteorological stations are few. Local observations can be a critical resource to understanding the impacts of climate change in these hard-to-reach areas.

2.4.3 Historical observations of climate in Mount Kenya and Mount Elgon

Explorer accounts of the two mountains provide the earliest record of climate on the two mountains. These can act as the first 'local' observations to create a baseline. The earliest explorers provided some ecological descriptions but no climate data (Ravenstein, 1891). Later accounts sometimes provide specific temperature readings - although the nature and setting of these thermometers is not known. The first European to reach the alpine zone of Mount Kenya was the Hungarian explorer Count Teleki, who with his assistant Lieutenant Hohnel explored the mountain in October 1887 (von Höhnel, 1894). These explorers noted that the temperature first fell to below zero at around 13,000 ft. (3962 m) and that there was a foot of snow on the ground at that point. A couple of years later, the explorer J.W. Gregory, recorded a temperature of -28° F (-33° C), at an unspecified elevation, but noted that it might be an error, and suggested that a more accurate reading is probably around 10° F (-12° C) (Gregory, 1896). Other observations of climate include a Dr. Loring who in 1909 recorded the snow commencing at 11,000ft (3353 m) and the permanent snow line at 15,000 ft (4572 m) (Roosevelt, 1910). Later J.W. Arthur in 1921 recorded temperature lows of 24-26° F (-3-4° C) at his basecamp in the Hausburg valley at around 14,000 ft (4267 m), and then 16° F (-9° C) at a higher camp at 15,000 ft (4572 m) (Arthur, 1921). For Mount Elgon, the historic records are much scarcer. Fred Lugard in his account of the mountain noted that frost at night can be expected at elevations about 10,000 ft (3048 m), but that there is no permanent snowline. However, 3 inches of snow were recorded during a 1919 expedition (Lugard, 1933). Another expedition recorded the presence of freezing water at 12,000 ft (3657 m) (Hancock & Soundy, 1931).

2.4.4 Cultural resilience

In modern times, mountain guides regularly traverse the mountains and can provide up-to-date accounts of mountain climate. Mountain tourism has become a large source of livelihood in Kenya, particularly for Mount Kenya (Chiyumba, 2015; Steinicke & Neuburger, 2012).

This means there is continuous observation of the upper alpine zone, and guides depend on being able to recognize the changing environment for their very survival. Indeed guides in other parts of the world have often provided critical and timely information on changing climates (Mourey et al., 2020; Purdie & Kerr, 2018; Salim et al., 2019).

For the communities surrounding the two mountains, keen observations of their surroundings form the basis of adaptive capacity - the ability of local communities to cope with changes in their environment. The term cultural resilience has gained traction in recent years, and refers to the inherent abilities of local communities to incorporate observations of change into a broader experiential and cultural framework in order to adapt to new situations. According to Davies and Moore (2016):

> *"Cultural resilience, as we understand it, is not a discrete property – something that societies or systems either possess or lack – but rather a set of contextually emergent attributes (thoughts, behaviours, knowledges, values and resources) that intersect across different social networks, identities, scales and institutions within lifetimes, across generations and through historical time….traditions and local perceptions of history not only constitute therefore a framework for continuity and stasis, but also provide the means for adaptation and change through normalising dynamic new actions and incorporating useful new environmental knowledge into mainstream consciousness"* (Davies & Moore, 2016).

2.5 Summary

Tropical alpine areas are important areas that provide critical ecosystem services both to local communities and to wider regional populations (Buytaert et al., 2011)The afro-alpine subset, found in the highlands of East Africa, has a unique climate, ecology, and socio-cultural setting that will influence how these areas respond to climate change. Afro-alpine areas are characterized by high diurnal temperature variation that creates for a freeze-thaw cycle on almost a daily basis (Hedberg, 1964). This in turn creates for an interesting assemblage of plant species with unique adaptations to this environment (Hedberg, 1964; Rehder et al., 1981; Smith & Young, 1987). It also allows the mountains to provide important ecosystem services such as biodiversity, water provision, and carbon storage (Buytaert et al., 2011).

Climate change is predicted to bring major changes to this socio-ecological system. Higher elevation areas are predicted to warm faster than lower elevation areas (Mountain Research Initiative, 2015; Rangwala & Miller, 2012) which may bring changes to the ability of the mountains to store and release water (Buytaert et al., 2006) and may force plant species to shift, adapt or face extinction (Isaac & Williams, 2007; Walther et al., 2005). Communities surrounding these mountains will be the first ones to experience these changes and their ability to survive will depend on their adaptive capacity (Abdul-Razak & Kruse, 2017; Gallopín, 2006). While much is known about the nature of afro-alpine systems and the types of changes that may occur, the data that exists is spotty and often conjectural (Chala et al., 2016; Loomis et al., 2017; Messerli & Winiger, 1992). Lack of long term, robust, in-situ data is the major data gap in studies of climate change in tropical alpine areas (ACCESS/IUCN, 2014; Buytaert et al., 2011). Because of this, fine-scale climate change models are lacking, prediction of future climate impacts is difficult, and designing appropriate adaptation strategies is near impossible (Buytaert et al., 2011).

Chapter 3 STUDY AREA AND METHODS

3.1 Location of the study area

Mount Kenya and Mount Elgon are located in central and western Kenya, respectively. They both are protected areas recognized for their valuable ecosystem services (Crafford & Strohmaier, 2012). Both are surrounded by high population density and rich agricultural land. Mount Kenya is an extinct volcano that last erupted some 2.6 million years ago (IUCN, 1997). It lies on the equator and its highest peak is at 5,199 m above sea level. Mount Elgon is a much older extinct volcano (12-22 million years old) that lies slightly north of the equator (1º N), and rises to 4,320 m (Wesche, 2002) (see Figure 3-1 and Table 3-1).

Table 3-1 Biophysical characteristics of Mount Elgon and Mount Kenya

Characteristic	**Mount Elgon***	**Mount Kenya+**
Superlatives	Largest volcano in tropical Africa covering 3500 km²	Second highest mountain in Africa (5199m)
Most recent eruption	12 million years ago	2.6 million years ago
Volcano type	Shield-like (Alkaline lava but not a true shield volcano^)	Composite Vesuvian volcano
Geology	rocks- tuffs, ashes, phonolites, nephlinites	basalts, rhomb porphyries, phonolites, kenytes and trachytes
LGM lowest glacial elevation	3350 m	2900 m
Current glaciers	No permanent ice	9 glaciers
Peaks	Wagagagi (4321m); Lower Elgon (4302m); Koitobos (4222m)	Batian (5199m) and Nelion (5185m).
Dominant Soils	Humic Nitosols (2100-3000m), Humic Cambisols (3000-3500m), Histosols/ Humic Gleysols (>3500m)	Ferric Luvisol/Humic Acrisol (2200-3000m), Humic Andosol (3000-3500m), Dystric Regosol (>3800m)
Temperature	19-23°C at base to 6°C at peak.	18-24°C at base to -5°C at peak
Precipitation (windward/leeward)	1500- 2500mm/yr (1500-2000mm/yr) on West side 1200-1800mm/yr (1200-1500mm/yr) on East side	1800-2300mm/yr (1500-2500mm/yr) on Southeast side 1000-1250mm/yr (700-1500mm/yr) on West/North side
Elevation max precipitation	2200-2600m	2500-3000m
Vegetation- Alpine zone	>3550m / (>3650m)	3650-4635m/ (3400-4500m)
Vegetation- Ericaceous belt	3300-3550m/ (3050-3650m)	3050-3650m/ (3200-3400- on S/SW)
Vegetation- Bamboo belt	2450-3050m/ (2800-3100m)	2400-3000m (on SE)/ (2700-3100m)

**(ACCESS, 2015; Kenya Water Towers Agency, 2020; Wesche, 2002)*
+(Baker, 1967; Bussmann, 2006b; Coe, 1967; Prinz et al., 2018; Schoorl et al., 2014; Speck, 1982)
^has general characteristics of a shield: broad volcano, runny alkaline lava (low silica), gentle slopes, but also is partly steep-ash cone with pyroclastics (Wesche, 2002)

3.2 Biophysical setting

3.2.1 Climate

The two mountains have similar climates, with the differences mostly being a function of geography and topography. For Mount Kenya, temperature ranges from an annual mean of 18-24 ºC at the base to -5 ºC at the peak (Coe, 1967). This amounts to a lapse rate of around 0.65 ºC/100 m elevation (Coe, 1967). Precipitation varies by elevation and aspect. The windward side of the mountain is the south and east side, and precipitation increases with elevation up to 3000 m before decreasing again towards the peak (Baker, 1967). On the leeward side, precipitation is at its maximum at around 2500m with 1000-1250mm/yr, declining to less than 700mm/yr in the lower elevations (Baker, 1967). There are two rainy seasons: a short rain in November-December, and a long rain in April-May (Speck, 1982).

Mount Elgon has a similar climate that varies with elevation and aspect. Mean temperature is similar at the base, but given that it is a shorter mountain, mean temperature at the peak is around 6 ºC (ACCESS, 2015). For Mount Elgon, moisture comes from the southwest (Lake Victoria) so precipitation is highest on the western slopes (ranging from 1,500-2,500 mm/yr), but the rain-shadow is not as great as in Mount Kenya, so the eastern side also receives anywhere from 1200-1800 m/yr depending on elevation (ACCESS, 2015). Maximum precipitation occurs between 2200 m and 2600 m on all aspects (Wesche, 2002). As with Mount Kenya, precipitation is bimodal with similar rainy seasons (ACCESS, 2015).

3.2.2 Vegetation

The vegetation of Mount Kenya is closely tied with the climate, and therefore with elevation and aspect. Vegetation zones change rapidly with elevation, and the nature and width of these zones varies from the drier north to the wetter south (Niemelä & Pellikka, 2004). In general, the vegetation transitions from cultivation at the base to montane forest on the lower slopes, and then bamboo, heather, alpine vegetation, and finally a nival zone of rocks and ice. The exact boundaries between these zones vary by interpretation, with different authors providing different elevations for zones or defining zones differently (Baker, 1967; Bussmann, 2006b; Coe, 1967; Niemelä & Pellikka, 2004). The most detailed zonation comes from Bussmann (2006), who provides elevation limits by aspect (Table 3-2). The lower slope montane forest (occurring anywhere from 1200 to 2700 m) is characterized by dense evergreen rainforests that include East African camphor (*Ocotea usambarensis*), Wild olive (*Olea capensis*), East African cedar (*Juniperus procera*), and Podocarpus (*Podocarpus falcatus*). This transitions into a bamboo zone at around 3000 m - coinciding with the zone of maximum precipitation. This zone is mostly a uniform thicket of Mountain bamboo (*Arundinaria alpina*), which then transitions into a cloudforest of *Hagenia abyssinica* and *Hypericum revolutum*. Then comes an *Ericaceous* zone dominated by heather species (*Erica* spp.). The Alpine zone begins somewhere after 3400 m is most characteristically known for its giant rosette plants (*Lobelia* spp. and *Senecio* spp.) and by a variety of cushion and scrub plants (*Helichrysum* spp. and *Alchemilla* spp.) as well as tussock grasses (*Festuca pilgeri* and others) Finally, a nival zone of rock and ice occurs above 5000 m (Bussmann, 2006b; Niemelä & Pellikka, 2004).

Table 3-2 Vegetation zones on Mount Kenya

Elevation (m.a.s.l)	**Zones**	**Dominant Species**
(2000– 2200) (only on W side)	Xerotropical deciduous open woodland	*(Acacia drepanalobium)*
(n/a on W and N) (1200-2500 on E) (1300-2500 on S/SW)	Supratropical mountain forest	*(Brachylaena huilensis, Croton megalocarpus; Ocotea usambarensis, Aningeria adolfi-friederici, Syzygium guineensis)*
(2200-2700 on W) (2500-2700 on E) (n/a on S/SW) (2000-2650 on N)	Orotropical montane forest	*(Cassipourea malosana, Podocarpus latifolius, Olea capensis); (Olea europaea spp., Juniperus procera)*
(2700-3000 on W; E) (2500-3100 on S/SW) (n/a on N)	Orotropical bamboo forest	*(Sinarundinaria alpina/ Podocarpus latifolius)*
(3000-3400 on W) (3000-3200 on E) (3100-3200 on S/SW) (2650-3000 on N)	Orotropical cloudforest	*(Hagenia abyssinica, Hypericum revolutum, Gnidia glauca)*
(3200-3400) (only on S/SW)	Orotropical ericaceous forest	*(Erica arborea)*
3400-4500 (from 3300 on E)	Altotropical moorlands/grassland and woodlands	*(Carex monstachya, Lobelia keniensis, Lobelia telekii, Dendrosenecio keniensis, Dendrosenecio keniodendron)*
4500-5000	Altodesertic cushion scrubs and herbs	*(Festuca pilgeri; (Helichrysum spp.)*
5000-5199	Subnival desert and nival zone	Rocks/ice

(Bussmann, 2006b)

The zones of Mount Elgon are similar, though there is less of a difference between aspects as on Mount Kenya (Hamilton & Perrott, 1981). Since there is less of a difference in rainfall by aspect, the bamboo zone extends around the whole mountain (Bussmann, 2006b). Otherwise the elevation limits of the bamboo zone, Ericaceous zone, and alpine zone are at similar elevations as on Mount Kenya (Table 3-2). Mount Elgon is not tall enough to have a true nival zone, however so the alpine zone extends to the top of the mountain (ACCESS, 2015;Wesche, 2002)

3.2.3 Physiography and drainage

Both Mount Kenya and Mount Elgon are considered principal Water Towers of Kenya (UNEP, 2009) (Figure 3-1). Mount Kenya is the source of water for all of north-eastern Kenya, providing water to over 10 million people, according to the 2019 census (Republic of Kenya, 2019). Most of this water (73% of dry season flow) comes from the middle and upper zones of the mountain (Kiteme et al., 2008). The entire drainage basins of the Ewaso Ng'iro and Tana rivers depend on the mountain, and these rivers feed several hydroelectric dams, particularly on the Tana River, before draining into the Indian Ocean (Ojany, 1993). Mount Elgon feeds the Nzoia and Turkwel river systems, which drain into Lake Victoria and Lake Turkana, respectively. These river systems provide water to another 9 million people (Republic of Kenya, 2019). It also is the source of water for the Kerim and Siranko rivers draining west into Uganda.

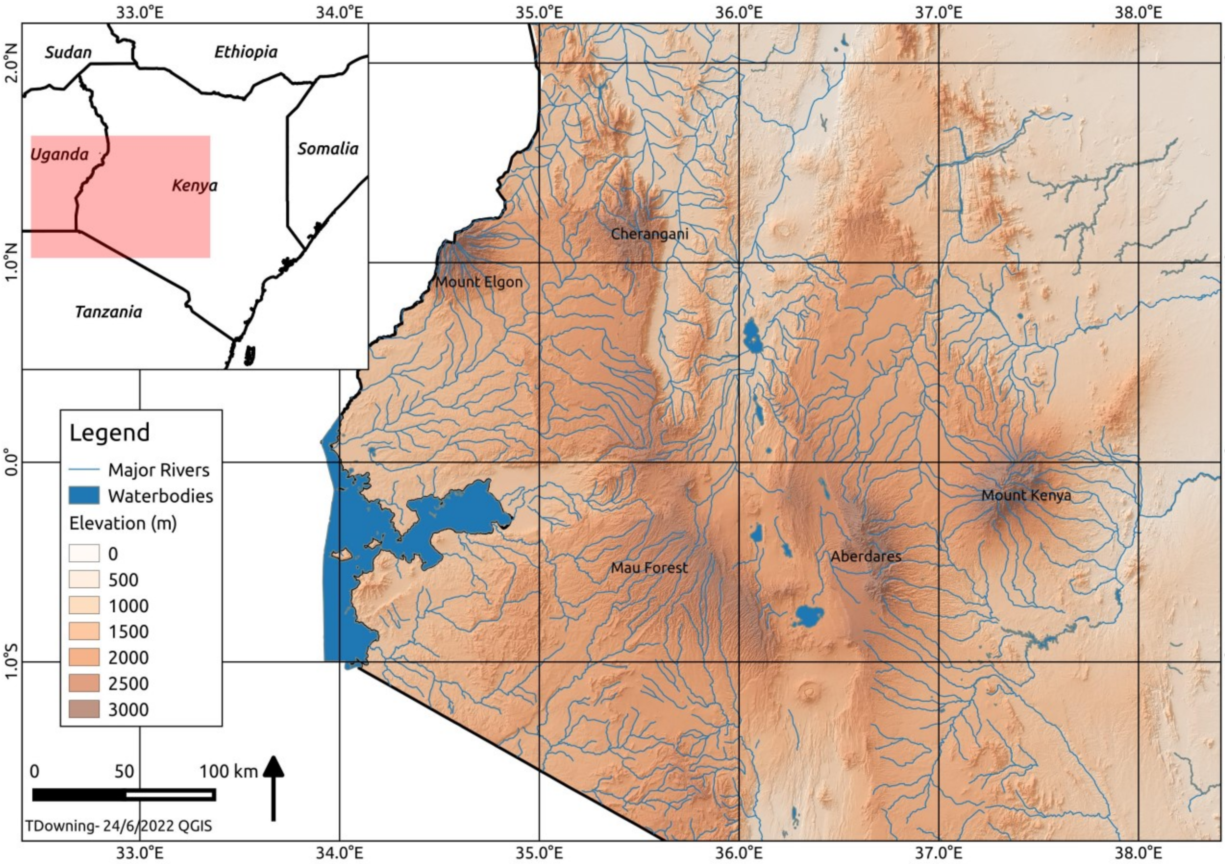

Figure 3-1 Physiography and drainage for central and western Kenya and the location of the five major water towers

3.2.4 Biophysical vulnerabilities

Mount Kenya and Mount Elgon are vulnerable bio-physically to climate change (UNEP, 2009). The two mountains, along with the other water towers, stand out as forest islands within a sea of agriculture and settled areas (Figure 3-2). These forests islands will be especially threatened by climate change given the unique sensitivities of the mountain environments (Kohler & Maselli, 2009). These mountains have very diverse ecosystems occurring over short distances (Körner, 2021). The amount of change that occurs latitudinally from the tropics to the poles, occurs in tropical alpine areas over the space of a few kilometres (Montgomery, 2006). A small change in temperature can therefore lead to significant changes in the boundaries of these ecosystems, affecting a suite of other variables including precipitation, humidity, soil properties, plant recruitment, competition, fire, and herbivory (Anthelme et al., 2014; Chala et al., 2016). Temperature changes can also lead to longer-term impacts on soil, hydrological, and climatic patterns as these processes are all partly controlled by temperature (Buytaert et al., 2011).

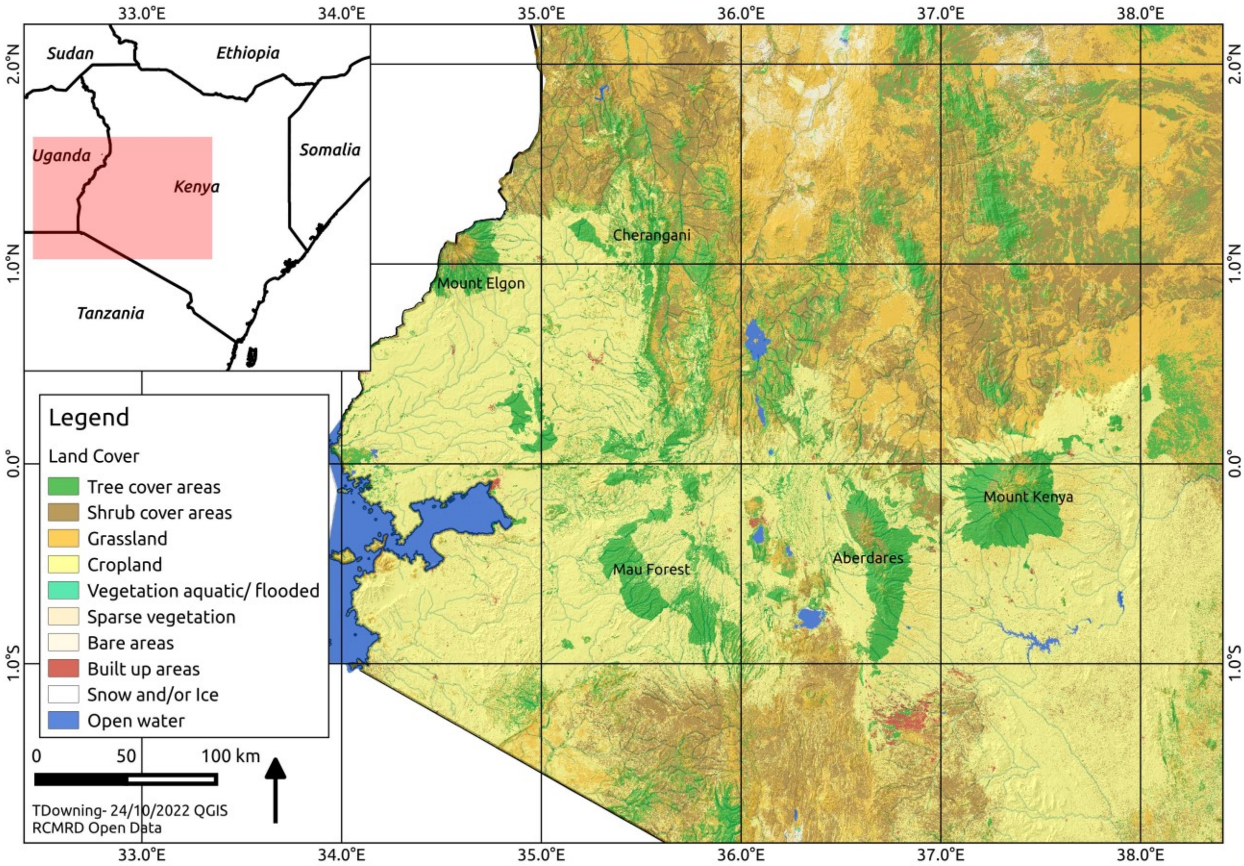

Figure 3-2 Landcover of central and western Kenya surrounding the five major water towers

Mount Elgon and Mount Kenya may have different sensitivities to climate warming and respond in different ways (Kohler & Maselli, 2009). Mount Elgon is a much shorter mountain, so as species move up in elevation in response to warming, they will run out of space more quickly (Chala et al., 2016). Mount Elgon is also a much older mountain with greater species diversity and endemism, but also with much greater isolation (Gehrke & Linder, 2009). The potential loss of biodiversity in Mount Elgon is therefore much greater. Hydrologically, Mount Elgon may be more vulnerable as it lacks glaciers: melting glaciers can help maintain baseflow during times of lower precipitation (Kaser et al., 2005). On the other hand, Mount Kenya experiences higher levels of use in the alpine zone from the higher levels of tourism (Steinicke & Neuburger, 2012), which can compound impacts of climate change..

3.3 Socio-economic setting

3.3.1 Political and administrative context

Under Kenya's new constitution in 2010, the county was made the principal administrative unit in Kenya, and most services were devolved to it (Republic of Kenya, 2010). This means that social and political functions such as health, agriculture, and solid waste management are overseen by the county governments. Each county is funded in part from their taxes, but largely from the national revenue in an equitable fashion (World Bank, 2012). With respect to environmental policies, there are still national ministries that oversee and coordinate policy, but it is up to the county governments to implement those policies (Muigua, 2018). Mount Kenya and Mount Elgon are both shared amongst several counties. Mount Kenya is located near the centre of Kenya and, reflecting its shared importance to the whole country, it is shared by no less than 5 counties: Meru, Nyeri, Tharaka-Nithi, Embu, and Kirinyaga - each of which has a sliver of the mountain (Figure 3-3). At the sub-county level this is even more pronounced, with 12 sub-counties each having a slice of the mountain - much like pieces of a pie.

The water coming off of Mount Kenya feeds a much larger area that includes Laikipia, Isiolo, Garissa, Wajir, Tana River, Kitui, as well as parts of Samburu and Marsabit. Mount Elgon, on the other hand, is located on the border with Kenya and Uganda with half of the mountain on either side. On the Kenya side, the mountain is shared by Bungoma and Trans Nzoia counties, and the drainage area fed by the mountain includes Busia, Kakamega, Siaya, West Pokot and some of Turkana counties (Republic of Kenya, 2019).

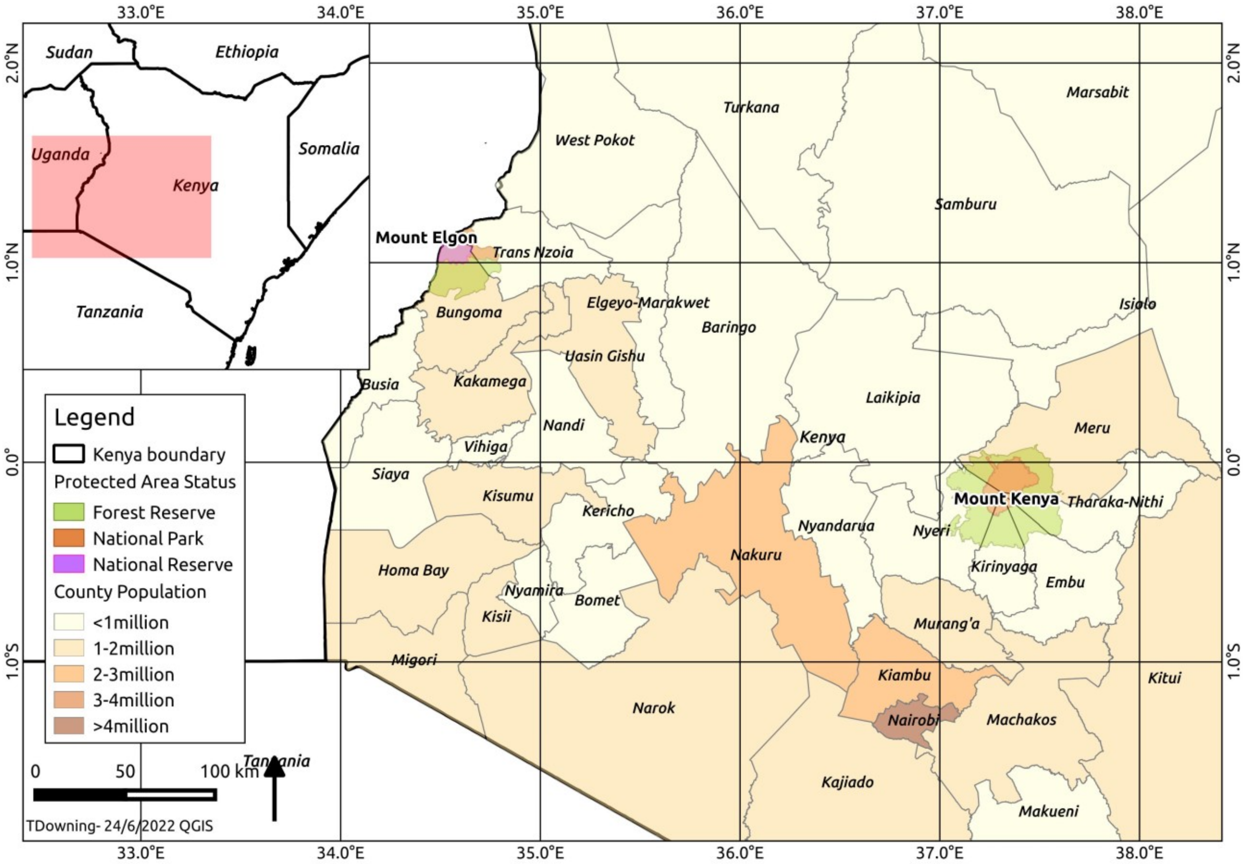

Figure 3-3 Population by country for central and western Kenya in relation to the study areas of Mount Kenya and Mount Elgon

3.3.2 Social context

Both mountains are characterized by a large and fast-growing population at their base. For Mount Kenya, the population of the counties that directly share the mountain comes to almost 4 million, according to the 2019 census, while the population of the entire water basins fed by Mount Kenya (the Ewaso-Ngiro basin and the Tana River basin) comes to over 10 million (Republic of Kenya, 2019). The average population density for the mountain counties is 246 persons/square kilometre, although to the south of the mountain it exceeds 400 persons/sq. km. The population around Mount Kenya expanded rapidly in the period after independence (Kiteme et al., 2008), but has since somewhat slowed down to an average annual growth rate of 1-2% (Table 3-3) (Republic of Kenya, 2019). The main peoples surrounding the mountain are the Kikuyu, Embu, and Meru people who are agriculturalists (Bett, 2005), while the pastoralist Samburu inhabit the area north of the mountain (Bussmann, 2006a). There are also some remnant communities of Maasai as well as people of European descent (Bett, 2005).

The population of Bungoma and Trans Nzoia counties, which share Mount Elgon, is around 2.6 million people with an average density of 475 persons/sq. km and an annual growth rate of 1-2% (Table 3-3) (Republic of Kenya, 2019). The people are largely Luhya, Teso and Sabaots with plenty of other tribes represented as well. Most (>80%) are involved in subsistence agriculture (Myhren, 2007).

Table 3-3 Population statistics for counties surrounding Mount Kenya and Mount Elgon (from 2019 National Population Census)

County	**Population 2019**	**Land Area (sq km)**	**Population Density 2019 (#/sq km)**	**Population 2009**	**Population change since 2009**	**Percent change per year**
Mt Kenya Counties	***3,917,065***	***17,194***	***228***	***3,459,455***	***457,610***	***1.32%***
Embu	608,599	2,821	216	516,212	92,387	1.79%
Kirinyaga	610,411	1,478	413	528,054	82,357	1.56%
Meru	1,545,714	7,006	221	1,356,301	189,413	1.40%
Nyeri	759,164	3,325	228	693,558	65,606	0.95%
Tharaka-Nithi	393,177	2,564	153	365,330	27,847	0.76%
Mt Elgon Counties	***2,660,911***	***5,519***	***482***	***2,449,691***	***211,220***	***0.86%***
Bungoma	1,670,570	3,024	552	1,630,934	39,636	0.24%
Trans Nzoia	990,341	2,495	397	818,757	171,584	2.10%

(Republic of Kenya, 2019)

In both mountains, agriculture is the main form of livelihood, mostly small-scale subsistence agriculture of maize and horticultural products (Bett, 2005; Myhren, 2007). Cash crops also exist, particularly coffee, which grows well at these higher elevations, but is mostly grown in a few large-scale farms (Myhren, 2007). The peoples also derive livelihoods from the forest itself - both legally and illegally - extracting resources such as firewood, building materials, herbs, and honey from the forest (Bett, 2005; Myhren, 2007).

3.3.3 Regulatory framework

Mount Kenya and Mount Elgon are both primarily managed by the Kenya Wildlife Service (KWS) and the Kenya Forest Service (KFS). These are parastatal agencies charged with managing the wildlife and forests of the country. KWS was created in 1990 and KFS in 2005. In both cases, the switch from a purely government agency to a parastatal was done to improve efficiency and accountability (Lake Victoria Basin Commission, 2010). The KFS was created out of the former Forestry Department under the Ministry of Environment and Natural Resources (later changed to Ministry of Environment, Water, and Natural Resources) under the Forest Act of 2005. The goal of this act was to encourage participatory forest management with local communities. This opened the way for the creation of Community Forest Associations (CFAs), which would work with the KFS to implement responsible utilization of forest resources under a permit system (Lake Victoria Basin Commission, 2010). Local involvement also comes through Water Resources Users Authorities (WRUAS), created through the Water Act of 2002 - these too provide local involvement in decisions related to water use and equitable sharing of this precious resource (Dell'Angelo et al., 2016). The KFS manages the National Forest Reserves, KWS manages the National Parks. The KWS follows a more strict conservation approach, allowing little to no resource use in the protected areas (Myhren, 2007). KWS also focuses more on tourism/recreation services and law enforcement. There are other parastatals such as the Nyayo Tea Zone, which is present in both mountains as a system of tree nurseries and plantations that serve as a buffer around the forest reserves themselves (Lake Victoria Basin Commission, 2010). Both mountains operate under a series of environmental policies that have been put in place over the years. These include the Forest Act of 2005, the 2008 National Environmental Policy, the 2013 National Climate Change Action Plan, the National Forest Policy of 2014, and the Forest Conservation and Management Act of 2016 (Muigua, 2018; Ongugo et al., 2014).

Mount Kenya is managed as one Forest Reserve and one National Park. The National Park was set aside in 1949 as the entire summit area - everything over 3,150 m - along with two tails covering portions of the two main hiking routes. The Forest Reserve then forms a circular ring around the National Park. It covers ~213,000 ha split into five different management zones and 23 forestry stations (Nyongesa & Vacik, 2019). The National Park covers ~71,000 ha and is accessed through 4 main gates (Naro Moru, Sirimon, Kihari, and Chogoria) with 2 other gates proposed (Kenya Wildlife Service, 2010). Mount Kenya has two guiding management documents, the Mount Kenya Forest Reserve Management Plan (2010-2019) and the Mount Kenya Ecosystem Plan (2010-2020). In line with their respective missions, the Forest Reserve Plan focuses on threats to the forest and resource utilization issues (Kenya Forest Service, 2010), whereas the Ecosystem Plan focuses on infrastructure and visitor use management (Kenya Wildlife Service, 2010).

Mount Elgon is under several different management regimes: the western portion is in Uganda, managed as a National Park, while the eastern portion is in Kenya and managed by several different authorities. The trans-boundary nature of the Mountain creates for unique challenges when it comes to manging natural resources (Petursson et al., 2013). The Kenyan part itself is divided into two Forest Reserves, one National Park, and a 'National Reserve'. The National Reserve - the Chepkitale Reserve - occupies a large portion of the moorland areas, and is held as a Trust on behalf of the local communities. It is managed by the Mount Elgon County Council as well as KWS. No permanent settlement is allowed in this reserve, but limited resource extraction is allowed, though not regulated. The two Forest Reserves cover ~73,000 ha and are managed through eight different forestry stations. The National Park covers ~17,000 ha and is accessed through one main entry gate (Myhren, 2007). The original inhabitants of Chepkitale were evicted (several times), and in return, a portion of the forest reserve was excised and given to them. This is the Chepyuk settlement area. Both Chepyuk and Chepkitale remain controversial issues (Lake Victoria Basin Commission, 2010).

3.3.4 Socio-economic vulnerabilities

The communities around both mountains are vulnerable to the changes in the bio-physical environment likely to be brought on by global warming (Kenya Water Towers Agency, 2020; Kiteme et al., 2008; Ojany, 1993; Ongugo et al., 2014). Mountain communities are typically more remote and more reliant on their immediate environment to meet their every-day needs than other communities. This can make them more fragile and marginalized, with fewer options for adaptation (Jodha, 2005). Communities surrounding both mountains are highly dependent on rain-fed agriculture and livestock (Bett, 2005; Myhren, 2007). The population density around these mountains is high, and the size of farms is very small (2-4 acres) (Myhren, 2007). These factors make these communities very vulnerable to changes in rainfall and streamflow. The communities also rely on the rich biodiversity of the mountain forests which will become threatened by climate change (Kenya Water Towers Agency, 2020). What's more, traditional adaptation strategies, involving local resources and collective sharing, are being lost due to globalization (Jodha, 2005). Communities thus have to find new ways to adapt in an increasingly uncertain environment.

3.4 Methodology

3.4.1 Research design

This study uses a mixed-methods approach to understand the impacts of climate change on the ecology and society of Mount Kenya and Mount Elgon, within a monolithic framework. The use of quantitative and qualitative methods, in combination, provides a better understanding of research problems than either approach alone (Creswell, 2013). Quantitative biophysical methods are used to analyse climatic and ecological patterns, while quantitative and qualitative socio-economic methods are used to analyse socio-cultural patterns. Vegetation and temperature patterns are examined in valleys representative of each alpine zone, then broader climatic and hydrologic patterns are examined for the western and southern slopes of the mountains, and finally socio-economic patterns are examined for the communities that fall within a 20 km buffer from the alpine zone. Since Mount Kenya is the mountain with the greater wealth of historic data, it is the dominant study area with Mount Elgon largely just used for comparison.

These analyses at different scales are then brought together inductively to find patterns and themes at each spatial scale. Patterns and processes are intricately linked: patterns give rise to processes which in turn influence patterns. Patterns occur in nested scales, whereby patterns at a local scale influence patterns at a regional or global scale (Hessburg et al., 1999). Moreover, there are inter-linkages between biotic and abiotic patterns and between the natural and the human dimensions. By investigating all these dimensions, one can begin to understand the full range of impacts of climate change in these unique areas.

3.4.2 Conceptual framework

The structure of the research is symbolically shaped like a pyramid - just as the mountains themselves (Figure 3-4). At the top of each mountain is the biophysical environment that creates ecosystem services supporting communities at the base of the mountain. There are then feedbacks between the biophysical and socio-economic environments: while biotic and abiotic factors on the top of the mountain produce and maintain ecosystem services on the mountain, communities and stakeholders at the base of the mountain use and also maintain these services through environmental stewardship. This closed system is then impacted by the external force of climate change, which impacts the abiotic factors that underlie the whole system. How the system is affected by these changes depends on the exposure and sensitivity of the mountain to these climatic forcings. Finally, local communities have an inherent adaptive capacity – based on their perceptions, practices and institutions - to mitigate this exposure and sensitivity.

This research explores the interface between science and society on the mountain through the transdisciplinary approach (Klenk & Meehan, 2015; Max-Neef, 2005; Pohl et al., 2021). Biophysical quantitative methods are used to understand the climate changes occurring on the tops of the mountains, and then socio-economic mixed-methods are used to understand the impacts of these changes on communities at the base of the mountains. The biophysical vulnerability (exposure, sensitivity, and resilience) informs the socioeconomic vulnerability (exposure, sensitivity, and adaptive capacity) (Füssel, 2007). The transdisciplinary approach assumes a continuous cycle of learning, where problems are constantly being framed, analyzed and explored, leading to formulation of new co-produced scientific questions. These questions in turn are explored, and in so doing give rise to new questions. This iterative approach is the bedrock of the transdisciplinary approach (Max-Neef, 2005).

Figure 3-5 outlines the different data sets and analysis methods utilized in this thesis. Biophysical vulnerability is assessed by investigating trends, variability, and patterns in climate data on the two mountains. Vegetation patterns on Mount Kenya are assessed by looking for evidence of shifting, extinction or adaptation. Finally socio-economic vulnerability is assessed by examining community perceptions on ecosystem services, changes in those services and ability for adaptation. The datasets used to support these analyses are climate time series data, in situ soil and temperature data, vegetation presence data, species morphological data, household questionnaires, focus group discussions, and key informant interviews.

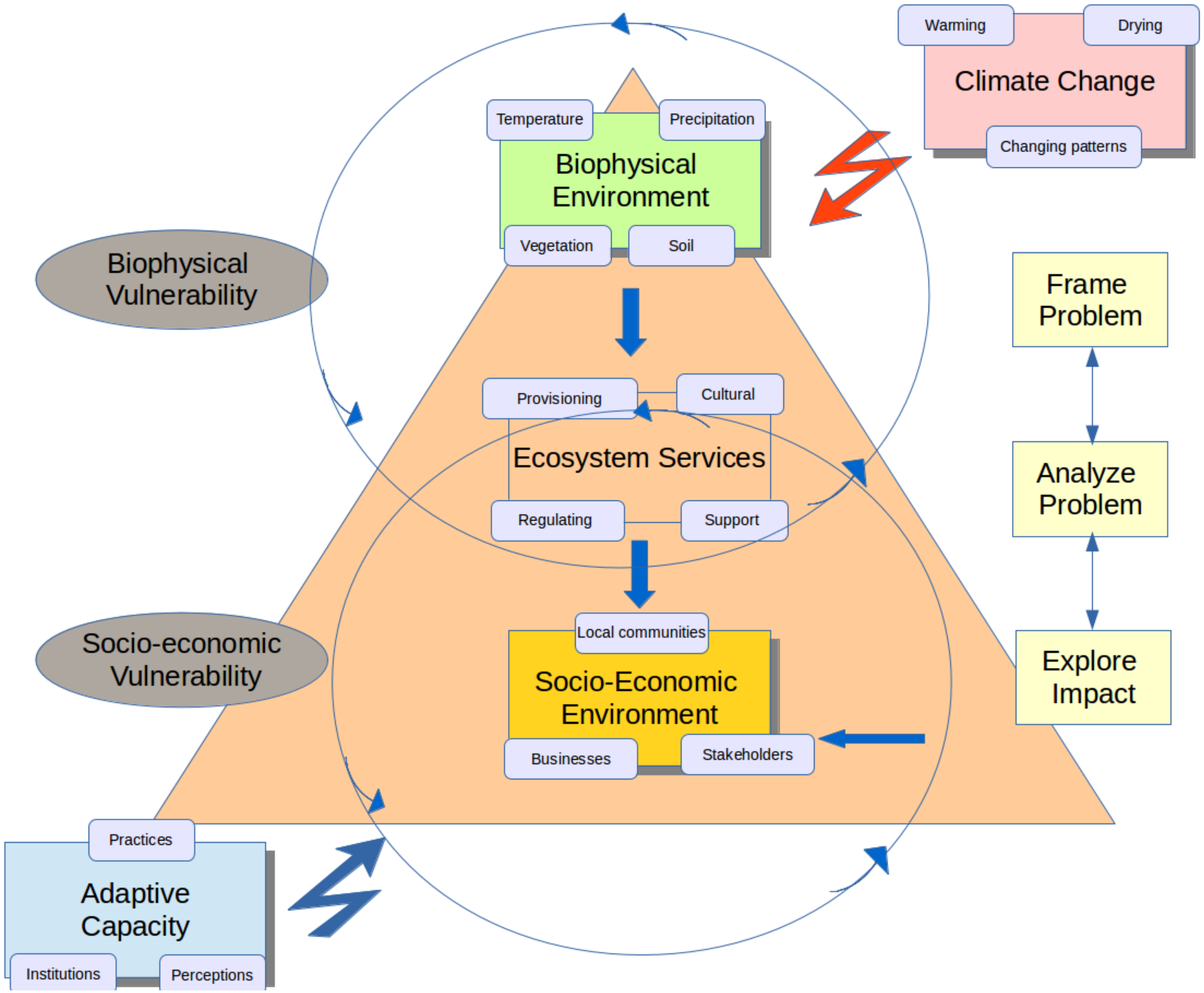

Figure 3-4 Conceptual framework for the current research

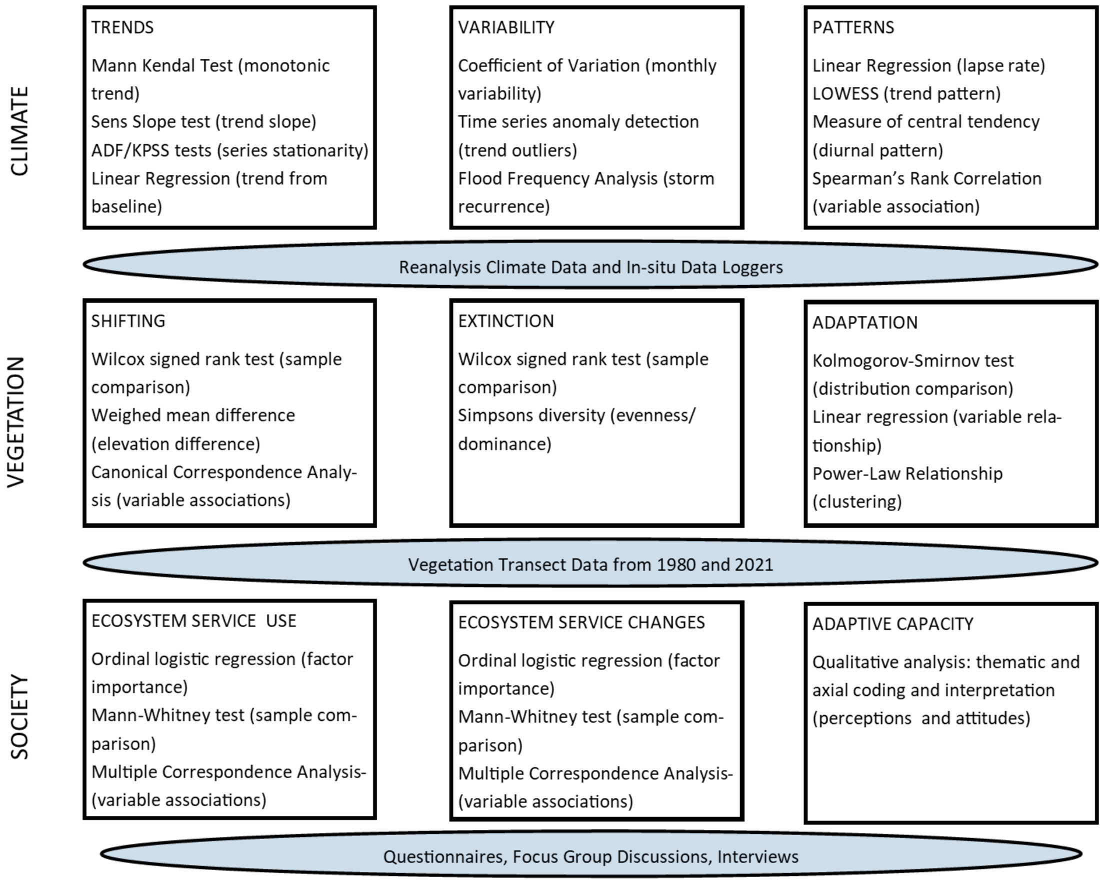

Figure 3-5 Summary of data and data analyses used in this thesis

3.4.3 Objective 1: Climatic Trends

3.4.3.1 Satellite data

There are several remotely sensed datasets for climate that combine satellite data with ground station data using a variety of interpolation techniques. These are known as Reanalysis datasets and they provide spatially and temporally continuous data with reasonable accuracy across the globe (Bao & Zhang, 2013; Mistry et al., 2022; Sun et al., 2018). Of these datasets, TerraClimate has the longest temporal coverage (since 1958) and also has a reasonable spatial resolution (0.04° or ~4 km), and temporal resolution (1 month) (Abatzoglou et al., 2018). TerraClimate data is available for free online, and the Famine Early Warning Systems Network has created a useful online application to allow extraction of time series data for any specified geographic area (FEWS NET, 2022; Ross et al., 2009). This site was used to download temperature and precipitation data from 1958 to 2021 for the Teleki and Koitobos valleys. Minimum Temperature (T_{min}), Maximum Temperature (T_{max}), Mean Temperature (T_{mean}) and Total Precipitation (P_{total}) were downloaded for the valleys on a monthly step. For broader scale mountain patterns in temperature and precipitation, time series data was collected along an altitudinal transect on each mountain. A series of 7 point were sampled every ~4 kilometers (according to the TerraClimate grid footprint) on the west side of Mount Kenya and on the south-eastern slope of Mount Elgon (Figure 3-6). At each of these points the full dataset was downloaded - 1958-2021 - at a monthly time step for T_{max}, T_{min}, T_{mean}, and P_{total}.

3.4.3.2 Stream gauge data

Stream gauge data for the major streams on the western and south-eastern slopes of the two mountains were obtained from the Kenya Water Resources Authority (WRA) (Table 3-4; Figure 3-7). There were the Rongai, Lower Sagana, and Muhuhi rivers for Mount Kenya, and the Malakisi, Koitobos, and Kuywa rivers for Mount Elgon. The gauge stations are all located at the foot of the mountains at approximately 2000 m.a.s.l (Figure 3-7). The data was obtained as daily discharges (m^3/s), and these were then converted to discharge on a monthly time step.

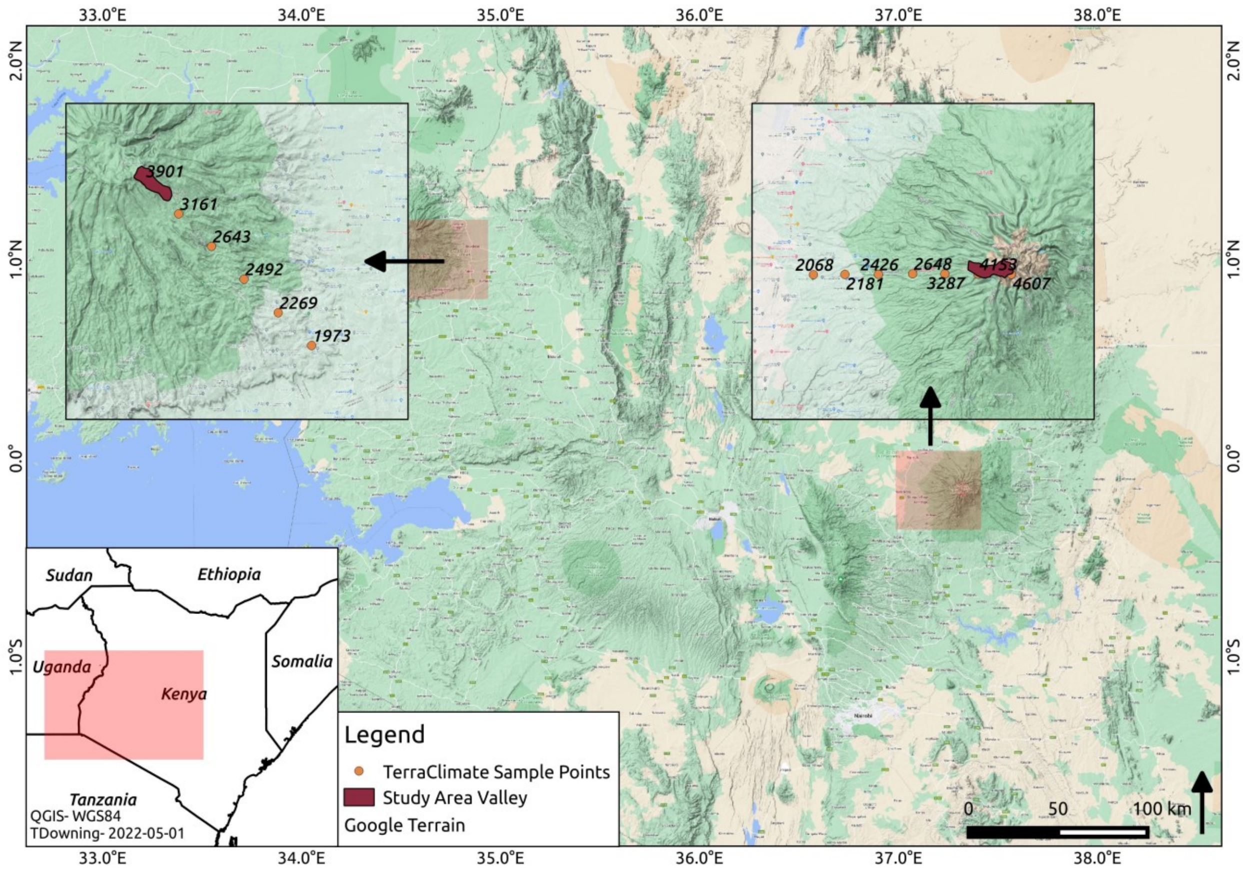

Figure 3-6 Sampling scheme for Mount Elgon and Mount Kenya using TerraClimate reanalysis dataset

Table 3-4 Major stream gauge stations around Mount Kenya and Mount Elgon downstream of the Teleki and Koitobos valleys

Mountain	Station ID	Stream Name	Elevation (m.a.s.l)	Period of Record
MOUNT KENYA	4BB03	Muhuhi	1927	1981-2002
	5BC05	Rongai	1950	1948-2019
	4AA06	Lower Sagana	2165	1960-1992
MOUNT ELGON	1AB01	Malakisi	1956	1978-2019
	1BE06	Koitobos	1895	1948-2003
	1DB03	Kuywa	1653	1978-1997

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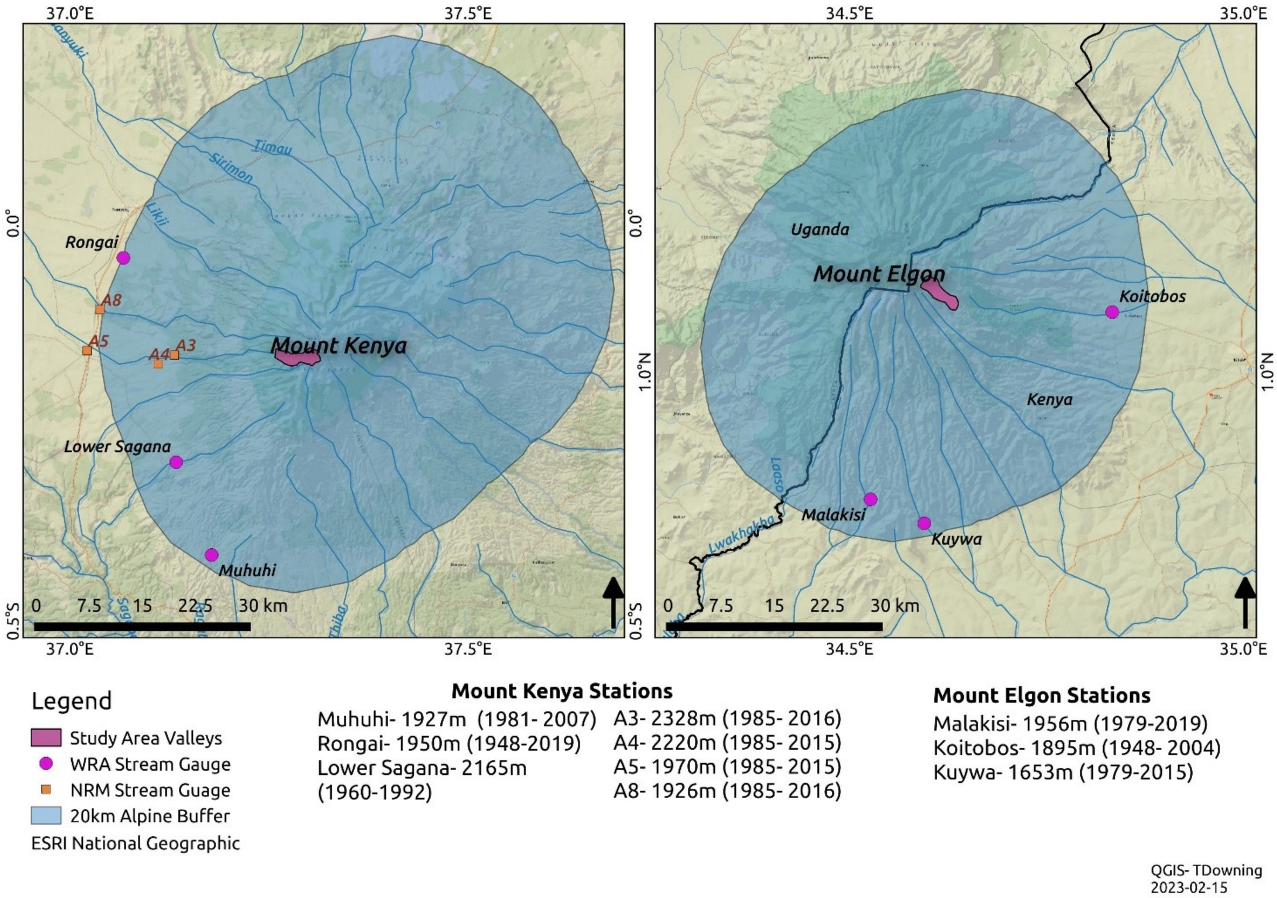

Figure 3-7 Location of streamflow gauge stations surrounding Mount Kenya and Mount Elgon

3.4.3.3 Ground station data - Mount Kenya

Ground station temperature and precipitation data for the western side of Mount Kenya were obtained from the Centre for Training and Integrated Research in ASAL Development (CETRAD). Most of this data is available on their online database (https://wlrc-ken.org/data/timeseries/index). This data was downloaded on a monthly time step for the stations surrounding Mount Kenya (Table

3-5). Daily temperature data was also obtained for the three main meteorological stations on Mount Kenya - Munyaka Station, Gate Station, and Met Station - by directly contacting the CETRAD offices. Stream gauge data was also obtained for the Naro Moru and Burguret streams flowing west off of Mount Kenya (Table 3-6). This data was obtained as gauge height data collected four times a day. A rating curve was obtained to convert these values to daily discharge values (Notter, 2003).

Table 3-5 Meteorological stations surrounding Mount Kenya

Name	**ID#**	**Elevation (m.a.s.l)**	**Lat/Long**	**Variables**	**Period of Record**
Teleki (Mt. Kenya) (NRM3)	ID#90	4262 m	37.29814, -0.16682	Precipitation	1978 – 2002
Naro Moru Moorland (NRM3)	ID#58	3771 m	37.242642, -0.164093	Precipitation	1990- 1995
Naro Moru Met Station (NRM3)	ID#62	3050 m	37.21392, -0.17060	Precipitation/ Temperature	1978- 2020
Naro Moru Gate Station (NRM3)	ID#61	2420 m	37.14797, -0.17445	Precipitation/ Temperature	1968-2012
Munyaka Station (NRM3)	ID#53	2070 m	37.0593, -0.183550	Precipitation/ Temperature	1991-2020
Ragati Forest Station	ID#77	2030 m	37.16005, -0.38053	Precipitation	1957- 2007
Kabaru Forest Station	ID#25	2237 m	37.15337, -0.28156	Precipitation	1959- 2007
Naro Moru Forest Station	ID#60	2364 m	37.13753, -0.21507	Precipitation	1965- 2003
Gathiuru Forest Station	ID#17	2330 m	37.11857, -0.09923	Precipitation	1959- 2004
Nanyuki Forest Station	ID#40	2337 m	37.14548, -0.06715	Precipitation	1989- 2004
Naro Moru FG Post	ID#59	2195 m	37.10191, -0.17634	Precipitation	1957- 1995
Hombe Forest Station	ID#20	1991 m	37.11583, -0.350675	Precipitation	1957- 2007

(CETRAD, 2022)

Table 3-6 Stream-flow gauges on the western slope of Mount Kenya

Name	**ID**	**Lat/Long**	**Period of Record**
Naro Moru Forest- North	A3	37.1311993, -0.1653287	1985- 2016
Naro Moru Forest- South	A4	37.1107382, -0.1766064	1985- 2015
Naro Moru Footzone	A5	37.0215789, -0.1598474	1985- 2015
Naro Moru Savannah	A6	36.9373784, -0.0636298	1985- 2015
Burguret	A8	37.0374994, -0.1084680	1985- 2016

(CETRAD, 2022)

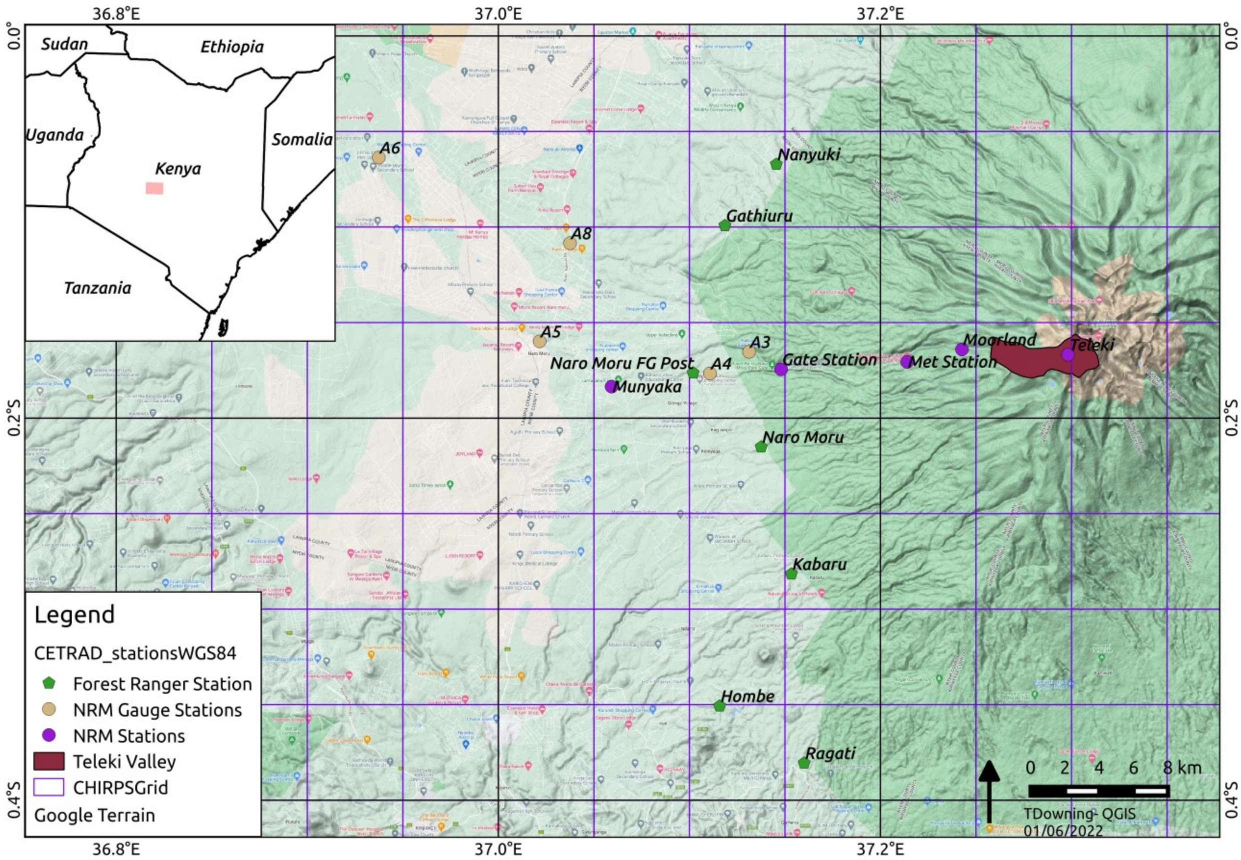

Figure 3-8 Ground meteorological stations on the western slope of Mount Kenya

3.4.3.4 In-situ data

In-situ data were obtained via temperature data loggers. The Onset Corporation produces relatively cheap loggers (HOBO U23 Pro V2), which can collect temperature and humidity data at any interval from 1 second to 18 hours, and can store up to 42,000 measurements. The battery lasts at least 3 years, depending on the logging interval, and the logger is durable and accurate at a variety of temperature ranges (Onset, 2022).

Loggers were placed in both study valleys - Teleki and Koitobos - starting from the 3200 m contour to the 4200 m contour, at 200 m elevation intervals (Figure 3-9). For Mount Elgon, however, the highest elevation logger was placed at 4100 m as the 4200 m contour was essentially the top of the mountain, which was mostly open rock. In Mount Kenya, an additional logger was placed directly beneath the Naro Moro Met Station at 3048 m for comparison purposes. Loggers were placed along the hiking trail in both valleys, but some distance from the trail itself to avoid being seen. Each logger was placed roughly at ground level (less than 20 cm from the ground) and zip-tied to the base of a shrub providing adequate shade throughout the day (see Appendix B1 for more placement details). The loggers were left to collect data at 30 minute intervals. These are similar procedures as described in other studies of in-situ temperature measurements in montane environments (Dolezal et al., 2016; Grab et al., 2004; Sklenář et al., 2016). At the 3600 m contour an additional logger was placed in each mountain immediately next to the first but with a solar radiation shield. Direct radiation on the loggers can overheat them, causing inflated temperature values; in some instances a radiation shield is recommended to mitigate this effect (da Cunha, 2015). Loggers ran from September 8, 2021 to February 8, 2022 on Mount Elgon, and from September 21, 2021 to February 22, 2022 on Mount Kenya. For Mount Kenya a second download was also done on November 8, 2022. In Mount Elgon, the lowest elevation logger (3200 m) could not be relocated during the February visit and was likely removed by hikers or herder.

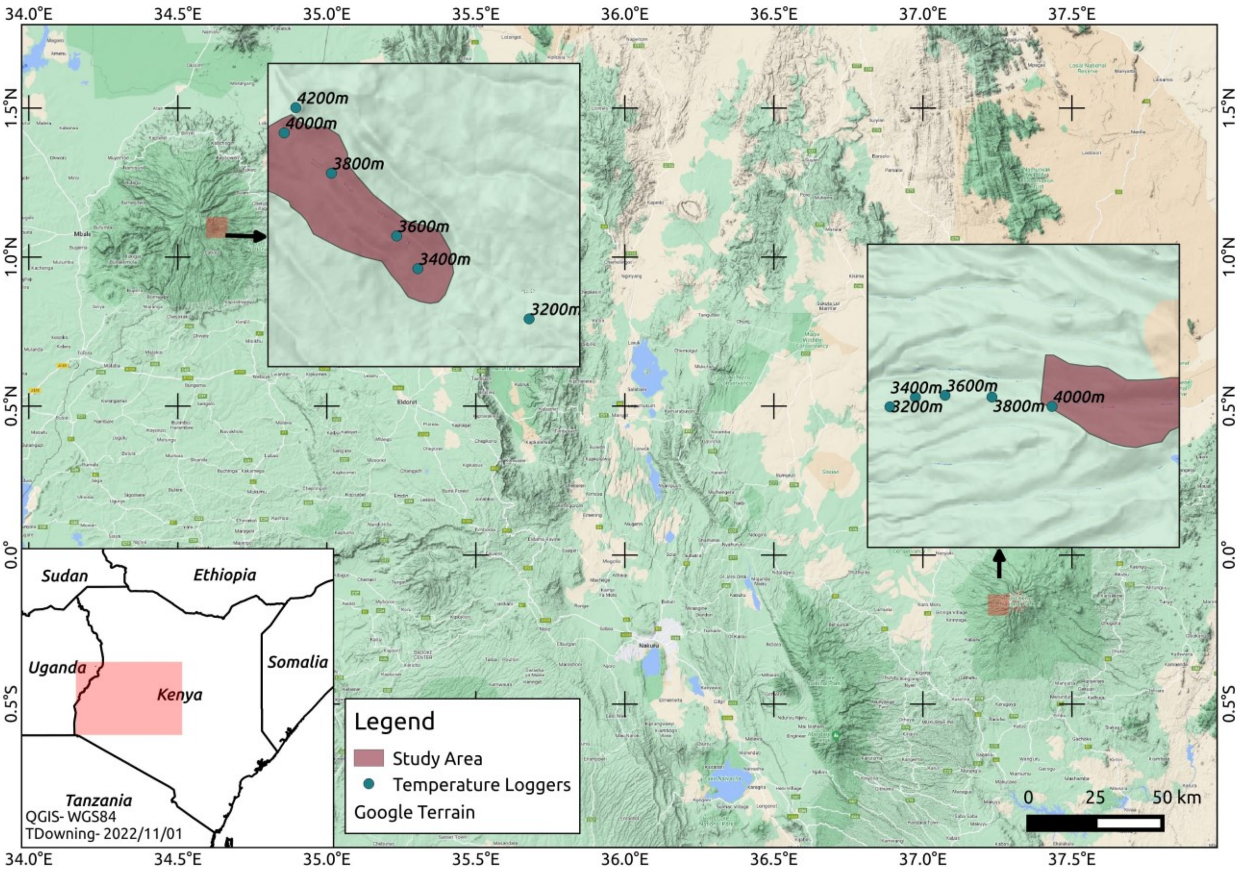

Figure 3-9 In-situ temperature logger placement in Mount Kenya and Mount Elgon

Twelve soil samples (six per mountain) were collected at the vicinity of each temperature logger from 3200 m to 4200 m. Samples were taken with an auger to a depth of 10 cm and then placed in polyethylene bags, labelled by the study site and contour interval. At each site, three different soil samples were taken and mixed together to get a representative sample of the area. The twelve soil samples were taken to the Kenya Agriculture & Livestock Research Organization (KALRO) laboratory in Kabete, Nairobi for a complete analysis of chemical properties. Parameters tested were: pH, exchangeable acidity (meq%), total nitrogen %, total organic carbon %, Phosphorus ppm, Iron ppm, Zinc ppm, Copper ppm, Calcium meq%, Sodium meq%, Magnesium meq%, Potassium meq%, and Manganese meq%.

3.4.3.5 Data analysis

Climate time series data were plotted and fitted with a LOWESS (Locally Weighted ScatterPlot Smoothing) trend line (Moran, 1984). The stationarity of each time series was determined using the Augmented Dickey-Fuller (ADF) Test and the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) Test (Wang, 2005). A stationary dataset is one with constant mean and variance over time and where seasonality is minimal (Prabhakaran, 2022; Witt et al., 1998). For ADF, the null hypothesis is that the data are non-stationary, whereas for KPSS the null is that they are stationary. If the data is not stationary, it can indicate an overall trend in the mean or variance. A Mann-Kendall test was used to test for the existence of such a trend - either upward or downward through time (here the null hypothesis is no monotonic trend in either direction) (Mann, 1945). The direction of this trend was then assessed with the Sens slope statistic (Sen, 1968). Variation in the series was tested using the monthly coefficient of variation, which was used to compare the two mountains (Asfaw et al., 2018). Lapse rates for the TerraClimate data were calculated as the slope of the regression line of mean temperature with elevation, and mean monthly precipitation with elevation. This was done using the centre elevation of each TerraClimate grid cell. The data was also broken out by decade as well to look for changes over time.

Discharge data for the WRA and CETRAD gauge stations were plotted as time series according to mean, maximum, and minimum discharge. Of particular interest was the minimum discharge - the low flow as that is the characteristic of most importance to surrounding communities. A flow frequency curve was fitted for the raw data using a Log Pearson 3 distribution (Bobee, 1975). Annual maximum discharges were extracted and sorted by order, and fitted with a cumulative probability curve. Recurrence time was then calculated as the reciprocal of the individual probabilities. Changes in recurrence intervals can illustrate persistent changes in the hydrological system. The A3 station on Mount Kenya was examined in particular detail, looking at trends in mean, maximum, and average discharge as well as anomalies from the raw data. This station is the highest elevation discharge station and therefore the most unaffected by human abstractions.

For the Mount Kenya ground-station data, a seasonal version of the Mann-Kendall test (Hirsch & Slack, 1984) was also utilized as seasonality was assumed to be a prominent component given the temporal resolution of the data. This seasonality was further investigated by separating out the data by season: December - February (DJF), March - May (MAM), June - August (JJA), and September - November (SOM). These correspond with the main rainy and dry seasons in Kenya. A linear regression was performed on the summarized seasonal data to check for significant trends. In addition, box plots of temperature and precipitation by month were constructed to examine intra-seasonal variability.

Ground station, satellite, and in-situ temperature data were compared at the Naro Moru Met Station. Monthly mean, minimum, and maximum temperatures were compared over the year (Jan 2021 –Jan 2022). Longer term trends were also compared: the Met Station data was plotted against TerraClimate and also against two other reanalysis datasets that were downloaded at this site. These are ERA5_Ag (ECMWF, 2022; Hersbach et al., 2020) and CFSR (Barnston & Tippett, 2013; Saha et al., 2010) (see Appendix A1).

Diurnal and seasonal temperature patterns were analysed from the in-situ data loggers. Mean, minimum, and maximum temperatures were calculated and summarized by hour, day, and month for each temperature logger. Temperatures were compared by elevation and by mountain, and also temperatures were compared for the 3600 m logger with and without the radiation shield. This was to examine the effect of direct solar radiation on temperature readings (da Cunha, 2015). Where applicable, statistical comparisons were done using the student's T-test. A temperature lapse rate was also calculated, by means of the slope of the regression line. Finally, soil chemical properties were plotted according to elevation and mean temperatures, and also compared with historical data. Comparisons between the two mountains were assessed by means of the student's T-test. Spearman's rank correlation values were calculated between individual soil parameters and mean, minimum, and maximum temperatures.

3.4.4 Objective 2: Ecological trends

3.4.4.1 Teleki Valley transects

The analysis of vegetation trends focused exclusively on the Teleki valley. A vegetation survey of the valley from 1980 was replicated as closely as possible in 2021 (see Appendix B for more details on this historical survey). Five cross-valley transects were placed at 1 km intervals going up the valley starting at 4000 m to 4400 m on the south ridge. Seven plots were sampled along each transect according to valley position: south ridge, south slope, south valley bottom, streamside, north valley bottom, north slope, and north ridge (Figure 3-10). Each sample plot (total of 35) was 30 m long, running perpendicular to the slope. Ten (10) 1 m x 1 m quadrats were laid down at three meter intervals, and the presence of each vascular species was recorded. This then created a species presence score on a 1-10 scale for each plot. In addition, all *Dendrosenecio* individuals (both *D. keniodendron* and *D. keniensis*) within 10 m of the plot centre-line were recorded. For the *D. keniodendron*, the height of each individual was recorded to the nearest half metre as well as the number of forks. Finally, environmental factors were recorded for each plot: slope, aspect, elevation, % rock, %bare ground/water, and % live vegetation.

Species identification was done through the help of a field guide, as well as input from the mountain guide and notes from the original study. Unfortunately the grasses could not be confidently identified as they were mostly in a non-reproductive state at the time of the year the field work was conducted, so grasses were dropped from the study. Grasses were similarly removed from the original dataset to allow for a valid comparison. Nonetheless a tally of grasses were still kept, grouped into two categories: tussock grasses and sedges. Also in each quadrat the species were listed in order of dominance (by % cover). For each plot, the most likely plant community was recorded, following the Rehder scheme (Rehder et al., 1988).

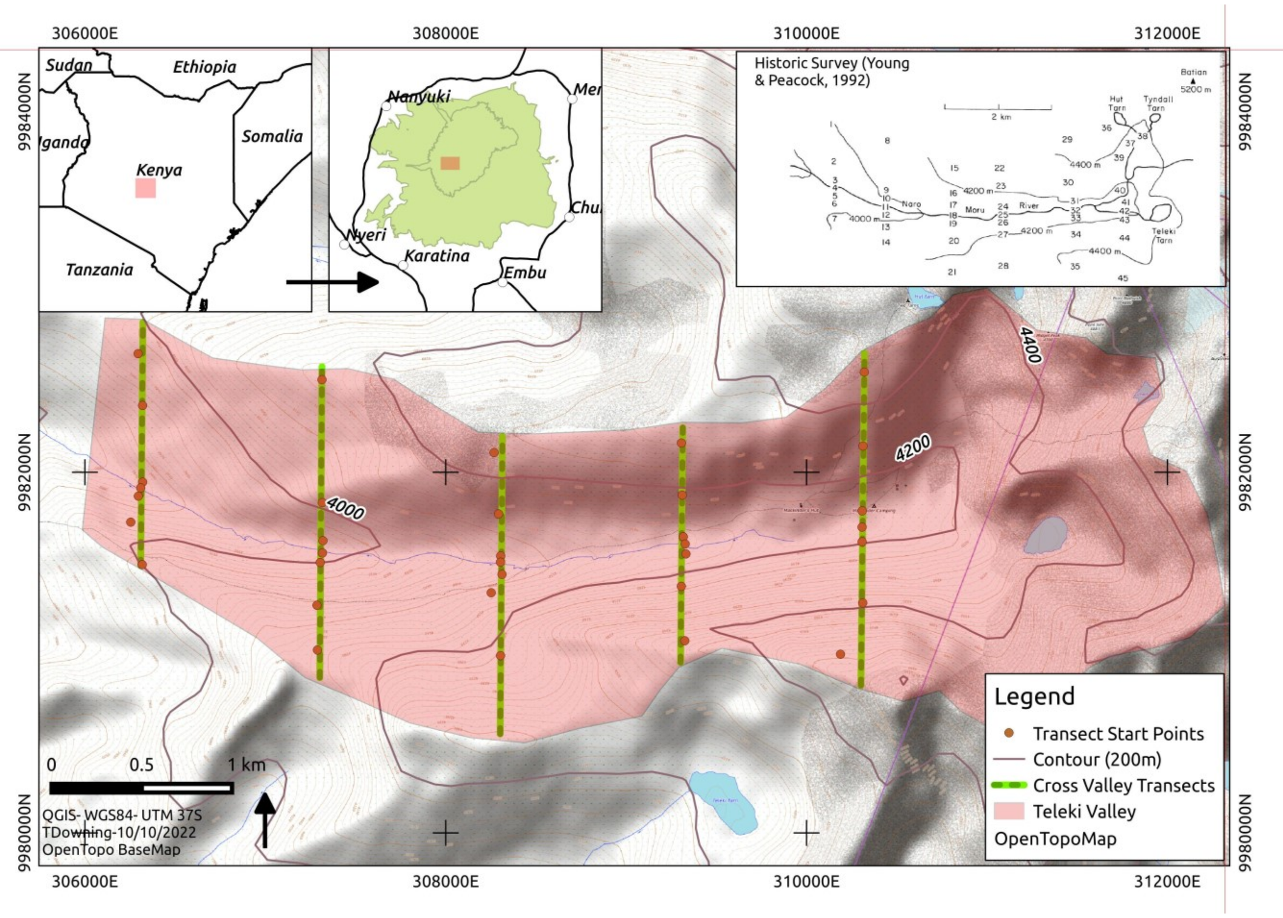

Figure 3-10 Study design at the head of the Teleki Valley, Mount Kenya (Downing et al., 2023a)

3.4.4.2 Landscape patterns

To investigate spatial patterns in Teleki Valley, a high resolution Plaeiades satellite image was obtained from June 6, 2018. This remotely sensed data was 50cm, 4 band, 16 bit imagery with <1% cloud cover; it was pan-sharpened and ortho-corrected by the vendor (Land Info Worldwide Mapping, LLC). The image was classified in a binary fashion into two classes – vegetation and non-vegetation and converted into vector format. At each of the sample plots, a 50 m x 50 m square was clipped from the classified image (Figure 3-11). This was then converted to tabular form in order to have a list of vegetation patches, by size, for each plot (see also Appendix A2).

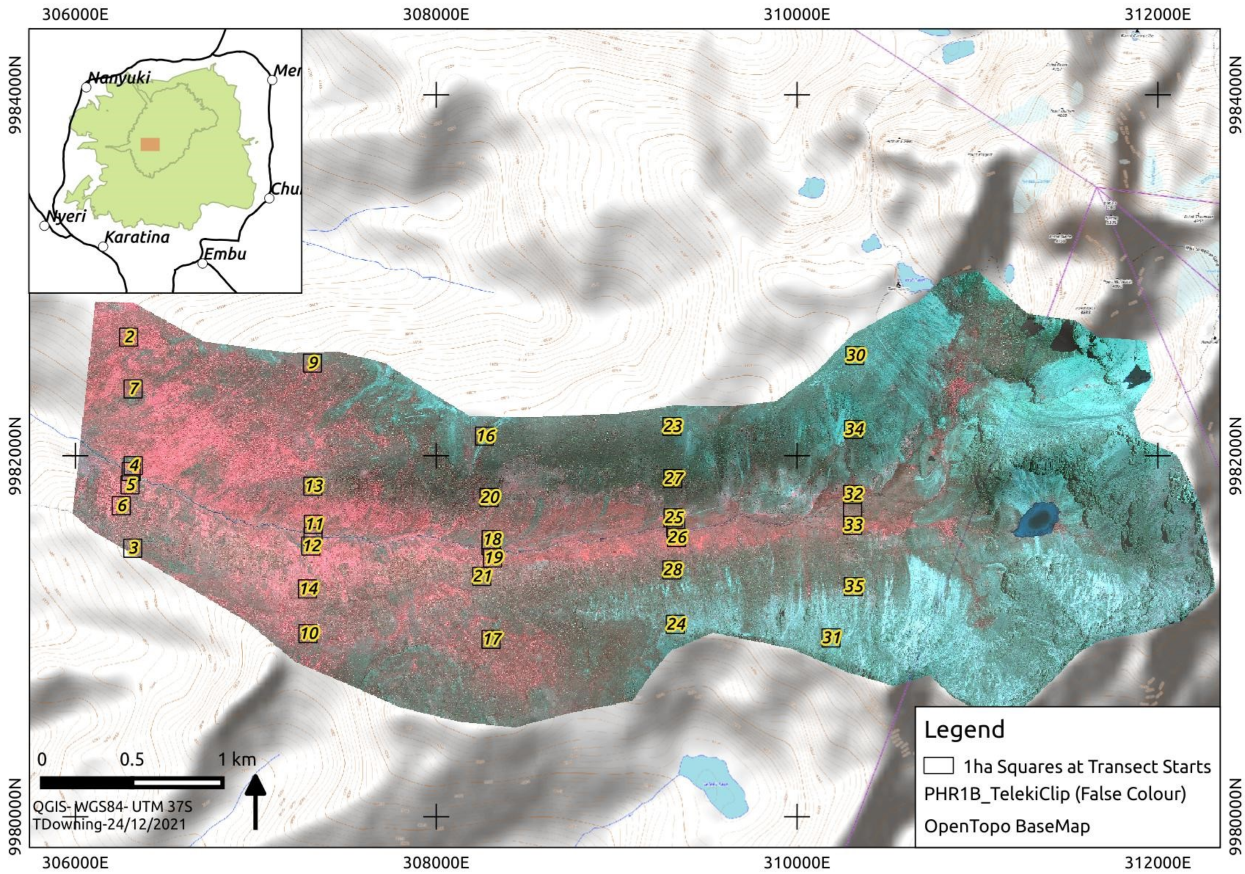

Figure 3-11 Satellite imagery of Teleki Valley, Mount Kenya and transect locations

3.4.4.3 Data analysis

The original survey from 1980 was done before the days of GPS, so it was not possible to perfectly relocate each site. Nonetheless, by stratifying the data by the underlying topographic gradients (elevation, slope, aspect), is was possible to statistically compare the two time periods (Kapfer et al., 2017; Zorio et al., 2016). Descriptive and inferential statistics were used to characterize the vegetation communities in both time periods and then compare them. The 1980 study relied chiefly on graphical methods to visualize relationships among the plant communities. The ordination and clustering methods revealed some interesting patterns that the authors explored further with scatterplots and linear regression (Young & Peacock, 1992). The current study replicates some of these original analyses. Additional analyses were also carried out, with the aim of identifying evidence of range shifts, compositional changes, diversity/dominance changes, and changes in relationships of plant communities to underlying environmental factors. Differences between the two time periods were then analysed with statistical tests for the paired sites. Table 3-7 identifies these analyses.

Table 3-7 Statistical analyses used to assess changes in vegetation communities from 1980-2021

Parameter	**Analyses**	**Comparison test 1980 vs. 2021**
Species richness and diversity	Mean number of species, Shannon diversity, and Simpsons diversity across the whole valley Simpsons diversity by valley position and elevation	Wilcox signed rank test Compare slope of regression line of diversity by elevation
Species dominance	Relative abundance of dominant species	Wilcox signed rank test Percent change in abundance
Species distribution	Frequency of dominant species by valley position and elevation Weighted mean elevation for all species	Wilcox signed rank test Shift in mean elevation per species
Environmental factors	Canonical Correspondence Analysis (CCA) of species and site relationships Non-metric Multidimensional Scaling (NMDS) of sites in both time periods plotted according to Bray-Curtis dissimilarity for paired sites	Comparison of CCA Biplot Scores Permutational Anova (PERMANOVA) for the two time periods
Abundance and distribution of Dendrosenecios	Density of the two species by valley position and elevation	Wilcox signed rank test
D. keniodendron population structure	Histogram of D. keniodendron height by valley position Scatterplot relationship between height and number of forks	Kolmogorov-Smirnov test to compare distributions Compare slope of regression line
Association between D. keniodendron and other species	Scatterplot relationship between D. keniodendron height and other dominant species	Compare regression coefficient

Both datasets were grouped according to three elevation classes and three valley position classes, which came out as the primary groupings in the cluster analysis from the original study (Young & Peacock, 1992). These groupings were ridge, valley, and mid-slope, and then low altitude (3850 m – 4050 m), middle altitude (4050 m – 4250 m), and high altitude (4250 m – 4450 m). Given how uncommon many of the species were, it was hard to make generalizations about rare species in either time periods. So, for comparison, the data set was reduced to those with at least 15% constancy - i.e. species who were found in at least 15% of the sites in both time periods (Zorio et al., 2016). Comparisons between the two time periods were done using the non-parametric Wilcoxon signed-rank test. Unless otherwise indicated, non-parametric tests were used because the frequency data did not conform to the assumptions of parametric tests - i.e. constant variance and normal distribution.

Relative abundance of the most constant species (15% constancy) was compared with the historical dataset. A weighted mean elevation was calculated for each species in both time periods. The difference in mean elevation then gives an indication of potential species range shifts (Elzinga et al., 1998; Felde et al., 2012; Lenoir et al., 2008). Species richness was calculated as the mean number of species per site, and diversity were assessed by Simpson's Index (Simpson, 1949). This is more of a dominance index to show to what extent sites are dominated by few species. Distribution of the dominant taxa were compared between the two time periods by elevation and valley position using the Wilcoxon signed- rank test. *Dendrosenecio* count data were similarly compared. Count data were converted into densities (numbers/100 m²) and then compared by grouped valley position and elevation class. For the *D. keniodendron,* histograms of counts by size class were conducted in total and according to grouped valley position, and compared between the two time periods. The relationship between number of branches and size class was also investigated in both time periods by comparing the slope and fit of the linear regression line.

The difference in importance of environmental factors was assessed by comparing the biplot scores of the Canonical Correspondence Analysis (CCA) (ter Braak, 1987) from both time periods and also calculating the Bray-Curtis dissimilarity between the paired sites and then visualizing the change in NMDS ordination space using arrows to indicate movement over the two periods with respect to environmental factors (Zorio et al., 2016).

Vegetative clustering was also analysed for the 35 transect sites by analysing the patch-size distribution from the classified satellite imagery. This was following the procedures of Berdugo et al. (2017) who has shown that the Power Law Range (PLR) statistic is a useful metric for quantifying vegetation distribution patterns. This statistic captures the shape of the distribution of patch sizes in the area. A high PLR value means that there are few, large patches, whereas a low PLR value indicates many, small patches. This statistic therefore provides an indication of the relative importance of competition and facilitation at each transect (Berdugo et al., 2017). If competition is the dominant interaction then one expects an un-clustered pattern (low PLR), whereas if facilitation is dominant, one would expect a clustered pattern (high PLR). The PLR was calculated for each 50m x 50m square overlaying the 35 transects (see Appendix A2).

Finally, historical and current photographs were qualitatively compared. While the exact locations of the photos could not be recreated, most of the historical photos were taken from the Naro Moru trail or from near the Teleki hut (Mackinder's camp). By matching elevations, it was possible to roughly match locations. The head of the valley forms a bowl shape, and many researchers took pictures of the valley head with the peak in the background, as it provided a spectacular view. This scene, therefore, could be recaptured fairly well.

3.4.5 Objective 3: Socio-cultural trends

Socio-cultural trends for the two mountains were analysed using qualitative and quantitative research methods consisting of questionnaires, focus group discussions and key informant interviews. These were carried out in the communities surrounding the mountains and downstream from the Teleki and Koitobos valleys, focusing particularly on Bungoma and Nyeri counties on the southeast side of Mount Elgon and west side of Mount Kenya. A 20 km buffer of the alpine zone was chosen as a reasonable limit of communities most likely to interact with this zone (buffer shown in Figure 3-12). For Mount Elgon, this area fell into the Cheptais and Mount Elgon sub-counties of Bungoma County, and in Mount Kenya the target area was completely captured by the Kieni East Sub-county of Nyeri County.

3.4.5.1 Quantitative data (questionnaires)

Questionnaires were administered in this study area using a cluster sampling strategy (Thompson, 1990); a sample size of 207 was selected for the study areas, using the formula:

$$n = z^2 * (p * q)/d^2 * DEFF$$ (Umulisa, 2012).

A desired precision ***d*** of 5% with an estimated prevalence ***p*** of 10%, gives a sample size of 138, but since a cluster sampling strategy was used, a design factor of 1.5 was multiplied to give a total sample of 207 (Table 3-8). This DEFF factor is as per the recommendation of the SMART (Standardized Monitoring and Assessment of Relief and Transitions) Methodology (Umulisa, 2012).

Table 3-8 Sample size calculation for household questionnaires

Sample Size Paramters	***Value***	***Cluster Design Parameters***	***Value***
t- value	1.96	Clusters	25
prevalence (p)	0.1	No per cluster	10
non prevalence (q)	0.9	Total Households	79,235
desired precision (d)	0.05	Sample Interval	3169
Design Effect (DEFF)	1.5	Random Start	2144
Sample Size	207		

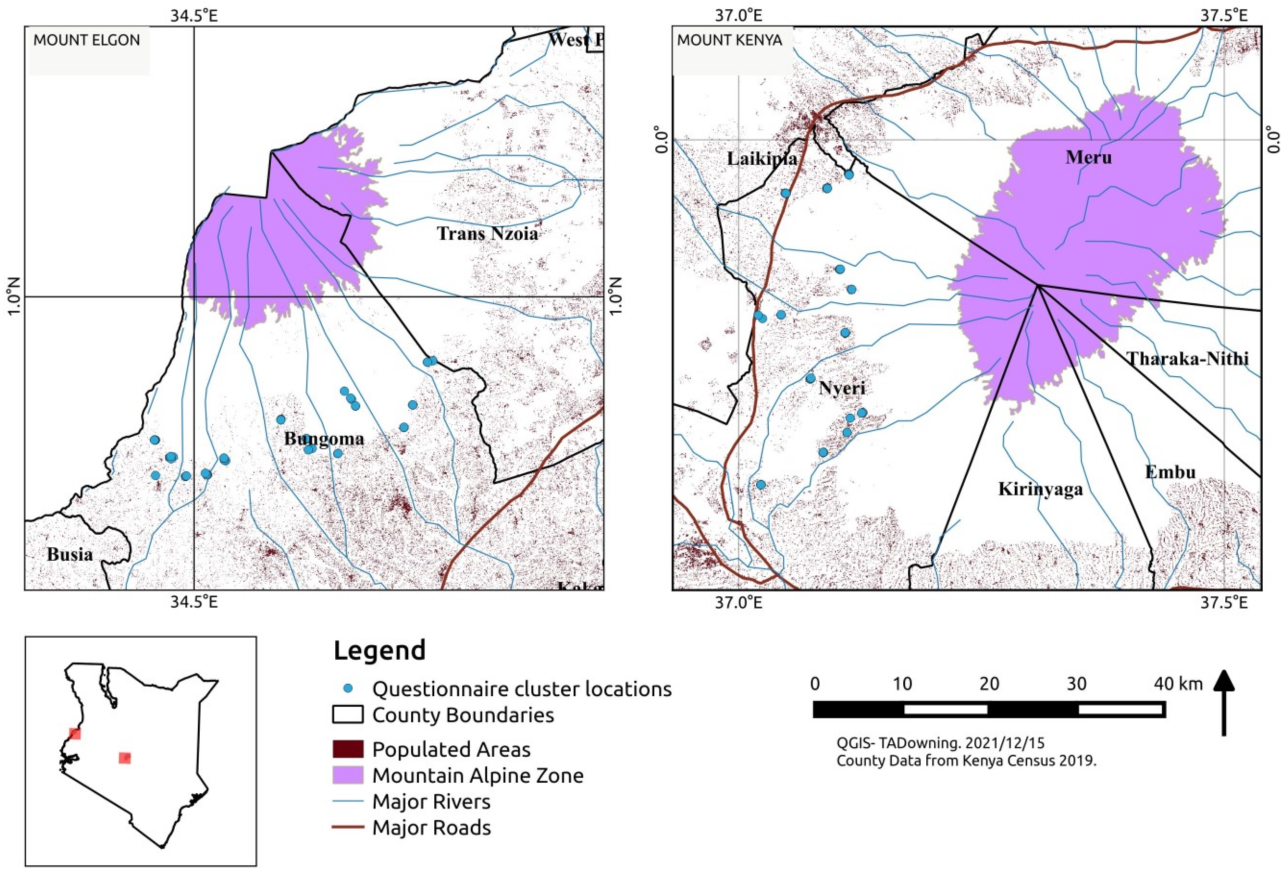

Figure 3-12 Questionnaire clusters for the two study areas - Mount Kenya and Mount Elgon

Based on this sample size, a total of 25 clusters was chosen. The sub-location was used as the sample unit, and clusters assigned with probability proportional to the population size of each sub-location according to the 2019 census data (Republic of Kenya, 2019). The number of households to be sampled within each cluster was determined again according to the population size based on a two stage selection strategy (Umulisa, 2012) (see also Appendix A3). For each chosen sub-location, questionnaires were administered in villages that were closest to the forest and within a small geographic area, to maximize on the 'cluster' aspect and minimize travel time.

A series of Likert scale questions (scale of 1 to 5) were used to quantify local views of the mountain and specifically the alpine environment. Questions dealt with 1) overall usage and knowledge of alpine resources; 2) importance of the alpine area; 3) changes experienced in ecosystem service delivery and 4) local adaptive capacity. These were assessed with different types of questions - some asking the respondent to record level of agreement with statements related to these topics, and others asking the respondent to rank importance and vulnerability of different ecosystem services (Appendix A3).

3.4.5.2 Qualitative data (Focus Groups and Interviews)

Two focus group discussions were conducted for each mountain with prominent local stakeholder groups (for details of each group see Appendix A3). These groups were a Community Forest Association, A Waters Users Association, a Mountain Guide association, and lastly a collection of youth from a high altitude herding community. Each focus group had five or six individuals selected by the groups themselves. These individuals represented a fairly homogenous but not totally uniform cross-section of the group; the goal was that each person would feel comfortable speaking, and yet also have something unique to contribute (Krueger & Casey, 2009). An appropriate venue was chosen beforehand and respondents were compensated for their time and travel. Each discussion was led by a moderator - the author or his field assistant - with a line of questions to guide the discussion (Appendix A3). Whoever was not leading the discussion acted as a note taker and participant-observer. The discussions were conducted in Kiswahili or English depending on the comfort level of the group, and were kept to around 1hour in length in order to keep the discussion focused and on topic. The discussions were recorded and then transcribed/translated afterwards.

Key informants interviews were also conducted with select individuals who were encountered during the administration of the questionnaires and identified as having extra unique knowledge on the mountains and the local environment (for a list of interviewees see Appendix A3). These interviews were about one hour in length. Interview protocols were used to trigger different topics, but the interviews were kept as unstructured and free-flowing as possible in order to give each interviewee the ability to talk about their particular expertise. Interviews took place in person at a venue convenient for the interviewee, and the interviews were recorded and transcribed.

3.4.5.3 Data analysis

Questionnaire data were graphically displayed through tables and charts. Demographic information was summarized tabularly for the whole study area and for each mountain. Likert scale data was presented as distribution curves and as horizontal bar graphs centred on the neutral response (value of 3). Percentages of ‘positive’ responses were tallied (values of 4 and 5) as were ‘negative’ responses (values of 1 and 2). Differences in responses between the two mountains were assessed with the Mann-Whitney test (Mann & Whitney, 1947). Ecosystem services were grouped according to the categories of provisioning, cultural, and regulating services. Since support services are not directly utilized by humans they were not considered in this study (MEA, 2005).

The factors influencing perception were assessed with an Ordinal Logistic Regression. Both spatial and demographic factors were considered as covariates. Demographic factors were gender, education, occupation, ethnicity, and immigration status; spatial factors were study area (Mount Kenya vs. Mount Elgon), distance to roads, and distance to the alpine area. The log-odds values for each factor was reported for each ecosystem service. Ecosystem services considered were water supply, raw material supply, medicines, livestock forage, food production, tourism, recreation, education, cultural heritage, wildlife habitat, water purification, nutrient cycling, and climate regulation. To test for multi-co-linearity, chi-square tests of independence were calculated among the different independent variables. The relationship between factors was also displayed graphically using a Multiple Correspondence Analysis ordination, and 95% confidence ellipses according to different explanatory factors. The data from the interviews and focus group discussions were analysed using qualitative methods. Coding for the interviews and focus groups was done surrounding the three main categories of ecosystem services, climate changes, and adaptive capacity (Figure 3-13). There were also codes for null statements of each of these categories: lack of services, lack of change, and lack of adaptive capacity.

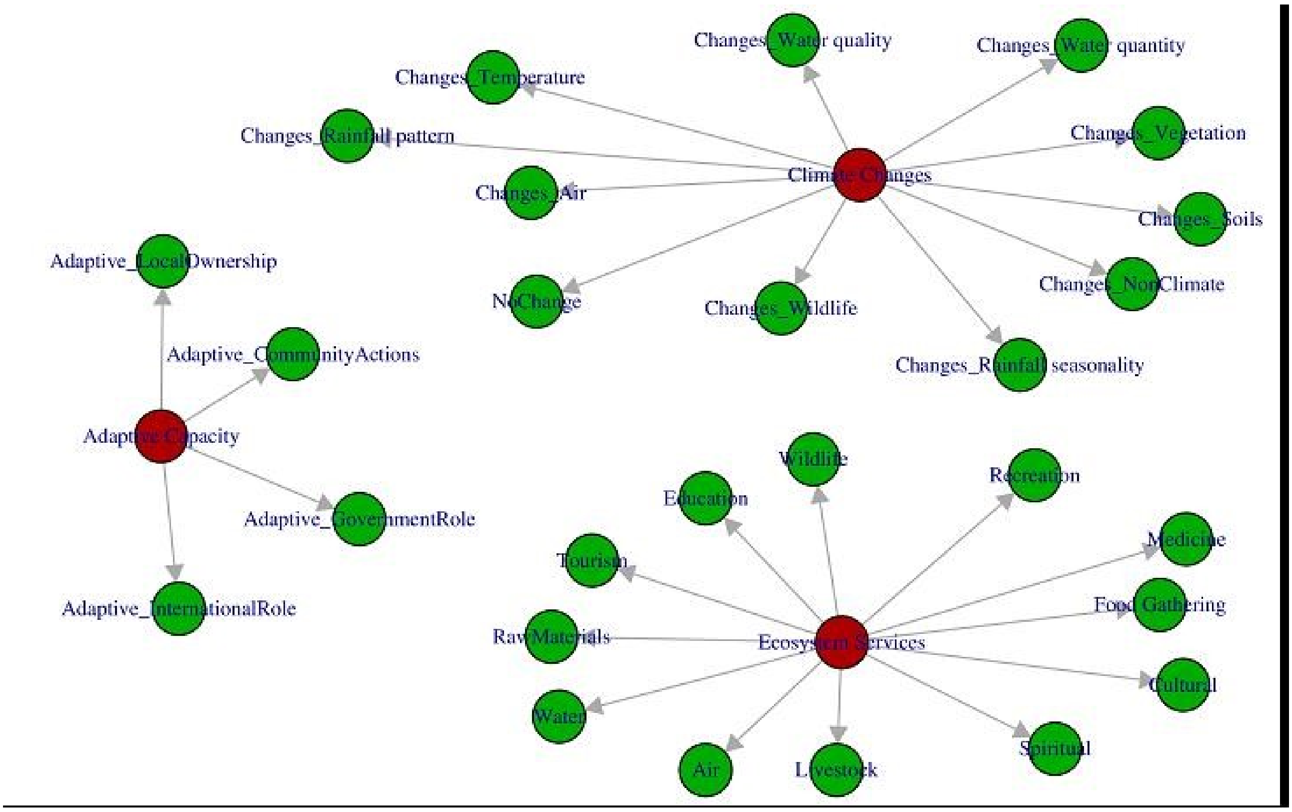

Figure 3-13 Thematic coding framework for the interviews and focus group discussions

3.4.6 Data Analysis Tools

All spatial analysis and maps were done with QGIS v. 2.8 (QGIS, 2022). Spatial data layers were obtained from a variety of online sources:

- Basemaps- Open Source basemaps (https://www.opentopodata.org/); ESRI National Geographic basemaps (https://www.arcgis.com)
- Census data- Kenya National Bureau of Statistics (https://www.knbs.or.ke/)
- Infrastructure- World Resources Institute (https://datasets.wri.org/)
- Landcover- Regional Centre for Mapping of Resources for Development (https://opendata.rcmrd.org/)
- Digital Elevation Model- Shuttle Radar Topography Mission (SRTM) (https://www.usgs.gov/)

Statistical analysis was done using R v. 3.6.3 using a variety of packages (R core team, 2022). Plots were mostly done with the *ggplot2* package, time series analyses used the *trend* and *forecast* packages, vegetation analysis using the *vegan* package, and the questionnaire analysis using the *EnQuireR*, *FactoMineR*, and *likert* packages. Qualitative analysis of interviews and focus group discussions was done using R Qualitative Data Analysis (RQDA) package (https://rqda.r-forge.r-project.org/). The relationships between code categories were then displayed graphically and used to generate over-arching theories on how communities interact with the alpine zone.

Data collection for the questionnaires was aided by the KoBo Toolbox (Kobo Inc., 2022), which is an open source set of tools for collecting survey data. The questionnaires were converted to a digital format using XLSForm (https://xlsform.org/en) and then launched from the KoBo website. Questionnaires were then administered in the field using an Android Tablet and the completed forms were uploaded to the KoBo website. Using the Tablet allowed for the addition of location data and photographs to complement the survey questions. Upon completion, the data was cleaned up on the website and then exported to tabular format for further analysis. Finally transcription of interviews was done using the Otter app (https://otter.ai/) which provides a decent first attempt at transcription for English language audio files.

3.5 Ethical aspects

This research complied with ethical standards and in conformance with Kenyan policies. A permit to conduct research was obtained through the Kenyan National Commission for Science, Technology & Innovation (License No: NACOSTI/P/22/15507). A permit to conduct research in the Mount Kenya and Mount Elgon National Parks was obtained from the Kenya Wildlife Service

(Ref No: WRTI-OOO4-01-21) and a Prior Informed Consent agreement was drawn up between the Kenya Wildlife Service and the University of Nairobi. Letters of research authorization were obtained from the Bungoma and Nyeri County Commissioner offices (Ref No: ADMIN,15/13.VOL.III/59 and NYC/ADM1/5.VOL.VII/(147) respectively). Finally verbal authorization was obtained from the Chief or Assistant Chief of each Location or Sub-location visited. All research participants were informed of the purpose of the research and provided informal consent. Participants who expressed interest were also provided early copies of the research results for their perusal and comment.

Chapter 4 CLIMATIC REGIMES OF MOUNT KENYA AND MOUNT ELGON

4.1 Introduction

This chapter describes the climatic regimes of Mount Kenya and Mount Elgon, looking at temperature, precipitation, and streamflow trends. First, temperature and precipitation trends are analysed for the two study area valleys using the TerraClimate reanalysis dataset. Then ground station data from the western slope of Mount Kenya, which has a higher temporal resolution, are explored in order to characterize seasonal trends. Next, the impact on streamflow is investigated by looking at streamflow trends around both mountains, but particularly Mount Kenya. Finally, in-situ temperature and soil characteristics from the two mountains are examined using data from the in-situ data loggers and the soil samples taken at the same locations. This data provides a fine scale look at daily and monthly temperature patterns on the two mountains and how this varies spatially and temporally. Values are also compared to historical records to assess how they have changed over time.

4.2 Results

4.2.1 Satellite Data- Koitobos and Teleki Valleys

4.2.1.1 Temperature/Precipitation trends

The TerraClimate dataset records show that mean monthly temperatures are increasing over time for both the Teleki and Koitobos valleys (Figure 4-1). The slope of the linear regression line (on a monthly time step) represents a warming of 0.24°C/decade for Teleki and 0.28°C/decade for Koitobos. Koitobos, which is a lower elevation valley (3300 - 4100 m), overall is roughly 2 degrees warmer than Teleki (3800 - 4600 m). The stationarity of the trends are mixed: while the Augmented Dickey-Fuller (ADF) test concludes that the time series for both valleys are stationary ($p<0.05$); the KPSS test concludes the opposite ($p<0.05$). This implies the data does indeed have a trend, yet does not have a unit root. This can sometimes occur either for ‘persistent’ series (Triacca et al., 2014) or if there is a small random walk component (Habibah et al., 2017). However a variance ratio test of the two series provides a number close to one, indicating that the series are indeed non-stationarity. The Mann-Kendall test reveals a strongly significant monotonic trend for both valleys, and the positive Sen’s slope confirms that the trend is increasing with time (Table 4-1).

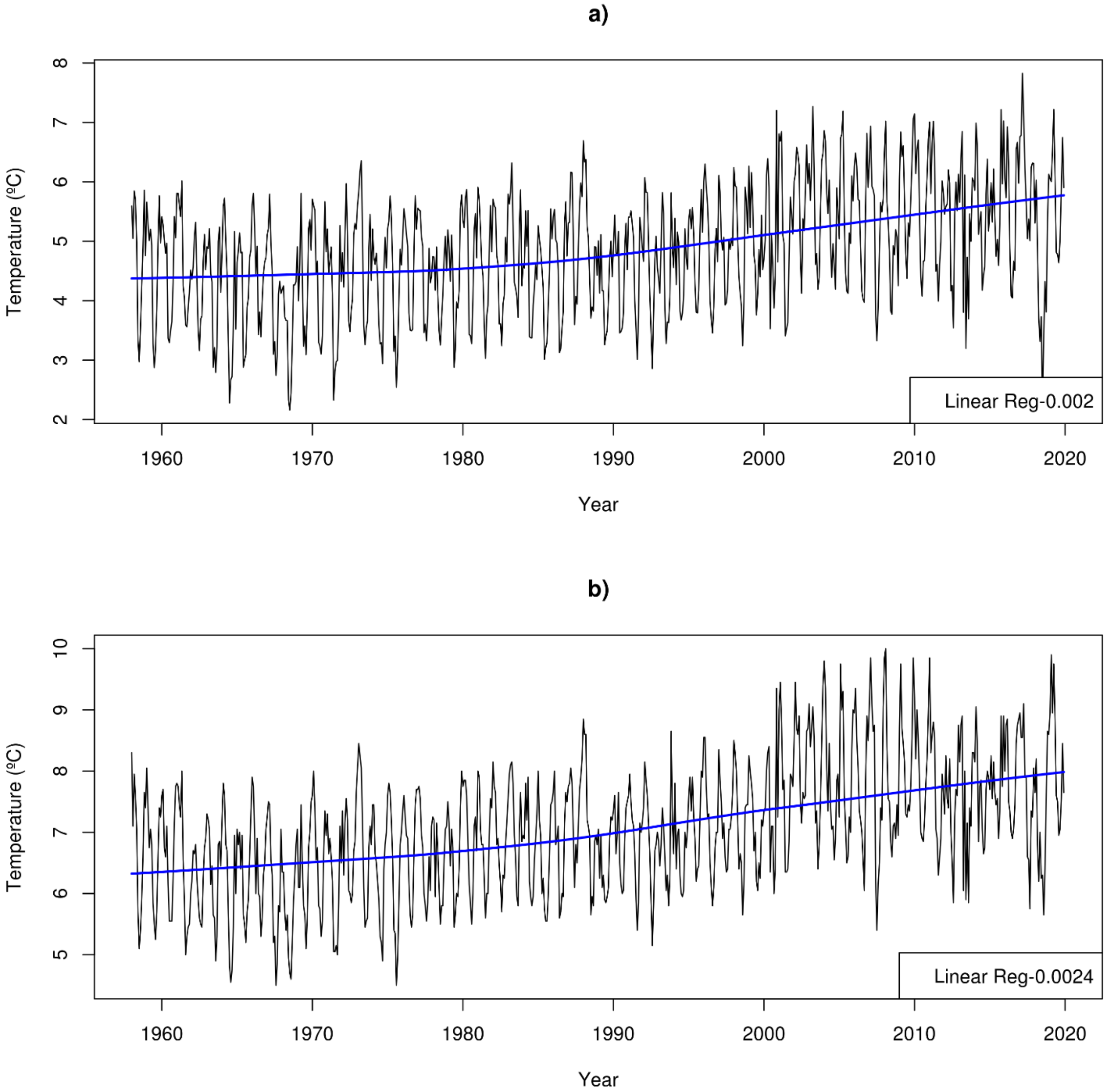

Figure 4-1 Terra Climate mean monthly temperature trends for the Teleki (a) and Koitobos (b) valleys of Mount Kenya and Mount Elgon, respectively. Trend is shown with a lowess line, and the slope of the linear regression line is indicated

The TerraClimate precipitation data, on the other hand, does not show any significant trends over the time series (MK $p<0.01$) (Figure 4-2). Monthly precipitation for both valleys, according to TerraClimate, is between 130-140 mm, with higher variability for Teleki Valley (Monthly COV 48.7 vs. 39.8). The value 30 is often used as a cutoff for highly variable rainfall (Asfaw et al., 2018), which suggests both valleys have high monthly variability. The time series for precipitation are stationary (ADF $p<0.05$; KPSS $p>0.05$), showing no unit root or any trend (MK $p<0.01$) (Table 4-1).

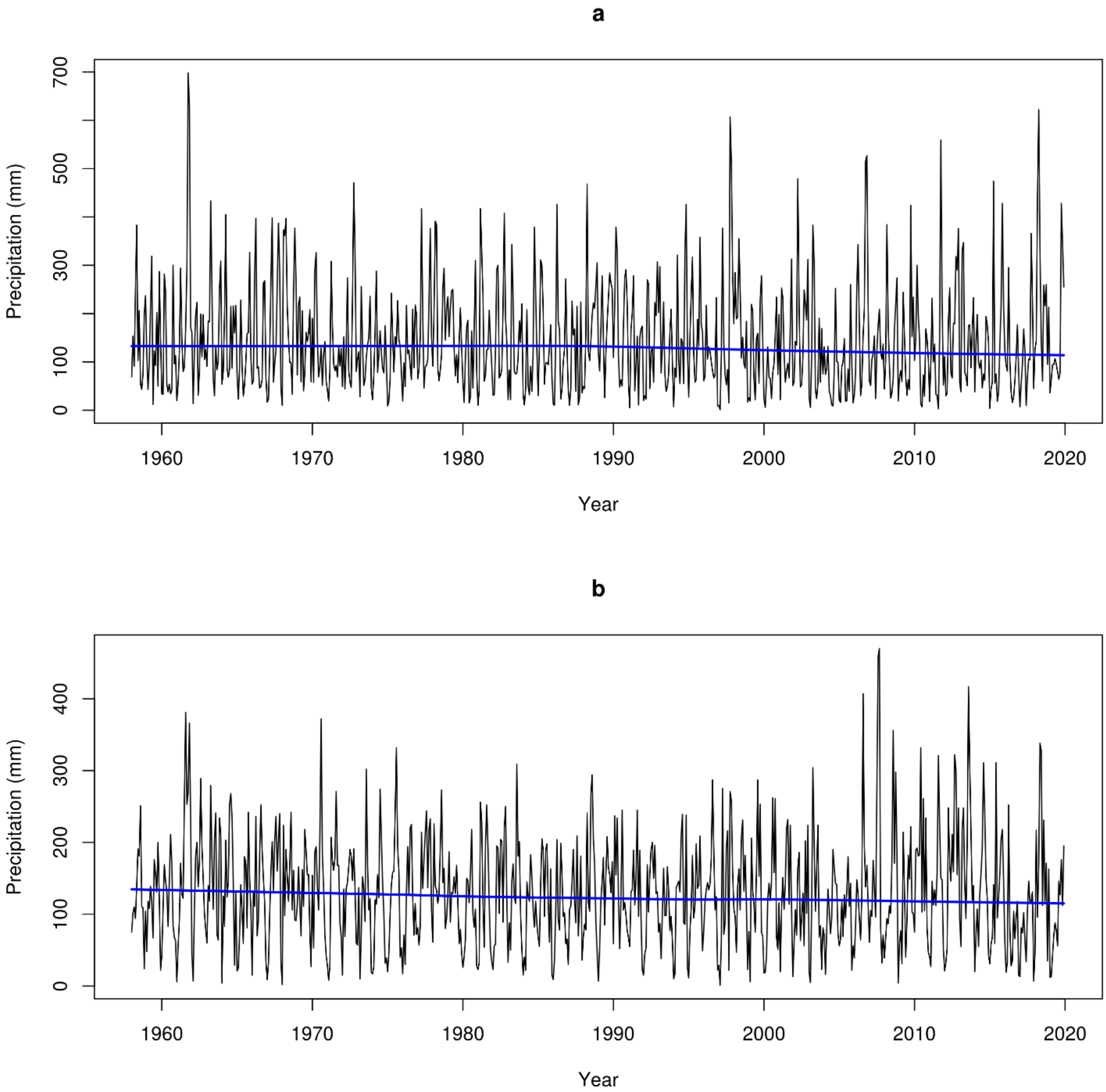

Figure 4-2 Terra Climate monthly precipitation trends for the Teleki (a) and Koitobos (b) valleys of Mount Kenya and Mount Elgon, respectively. Trend is shown with a lowess line

Table 4-1 TerraClimate Trends (1958-2020) from Teleki and Koitobos valleys

Valley	**Mann-Kendall Test (2-sided) (Null= No Trend)**	**Sens Slope (Slope/Direction of Trend)**	**Augmented Dickey-Fuller Test (Null= Not Stationary)**	**KPSS Test for Level Stationarity (Null= Stationary)**	**Monthly Coefficient of Variation**
TEMPERATURE					
Koitobos	**13.33 (p <0.01)**	**0.0024 (p <0.0001)**	**-6.05 (p= 0.01)**	**5.48 (p=0.01)**	**10.43**
Teleki	**10.74 (p<0.01)**	**0.0020 (p <0.0001)**	**-6.99 (p=0.01)**	**4.43 (p= 0.01)**	**16.25**
PRECIPITATION					
Koitobos	-1.48 (p=0.14)	-0.0183 (p=0.1400)	-10.03 (p=0.01)	0.08 (p=0.10)	39.80
Teleki	-1.33 (p=0.18)	-0.0204 (p=0.1825)	-9.47 (p=0.01)	0.10 (p=0.10)	48.72

4.2.1.2 Trends with respect to ENSO cycles

Precipitation patterns in the region are naturally expected by have a cyclical element over decadal scales due to the El Niño Southern Oscillation (ENSO) sea surface temperature phenomenon. These cycles have been tracked over time by the National Oceanic and Atmospheric Administration (NOAA) using the Ocean Niño Index (ONI) (Bamston et al., 1997; NOAA, 2023). Positive index values represent warm and negative values represent cool periods of ocean temperatures; values above or below +/-0.5 represent departures from normal. Graphing this index alongside precipitation in Teleki Valley shows an approximate correlation of precipitation with ENSO cycles- with high precipitation periods generally falling during periods of above average sea surface temperature (Figure 4-3).

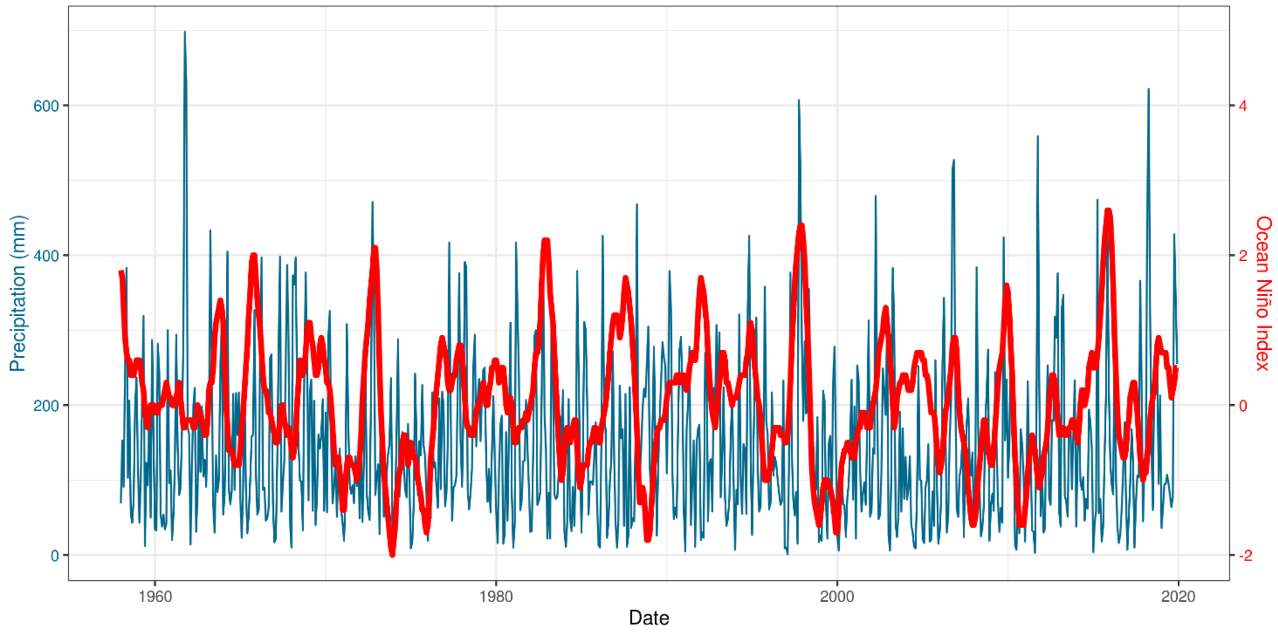

Figure 4-3 Terra Climate monthly precipitation for Teleki Valley alongside the Ocean Niño Index

4.2.1.3 Lapse rates

The TerraClimate data overall displays a temperature lapse rate of 0.50 °C/100 m for Mount Kenya and 0.59 °C/100 m for Mount Elgon (Figure 4-4). For both mountains, the slope of the line has not changed over the time series, but the position has shifted- each bi-decade is uniformly warmer than the previous one.

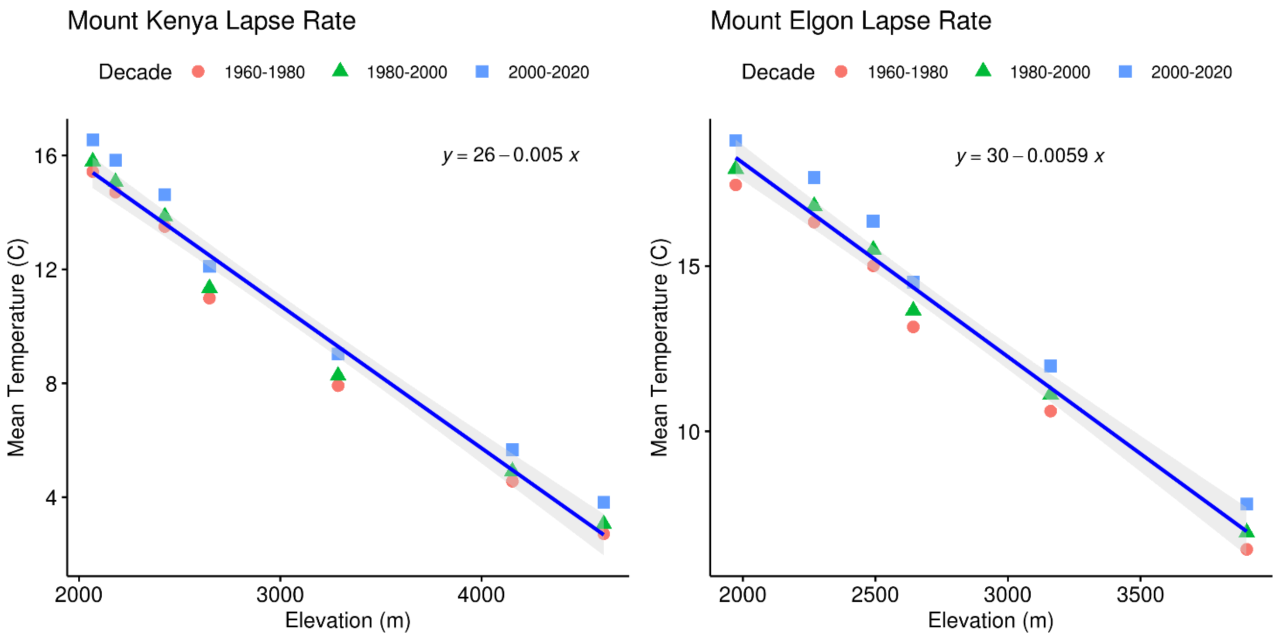

Figure 4-4 Temperature lapse rate on Mount Kenya and Mount Elgon according to TerraClimate

Precipitation patterns by elevation are different for the two mountains. For Mount Kenya there is a sharp increase in precipitation with elevation until 2800 m and then it levels off. For Mount Elgon, precipitation increases gradually with elevation with a maximum close to the peak at 3900 m. The 1960-1980 bi-decade was wetter than the overall average in both mountains (Figure 4-5).

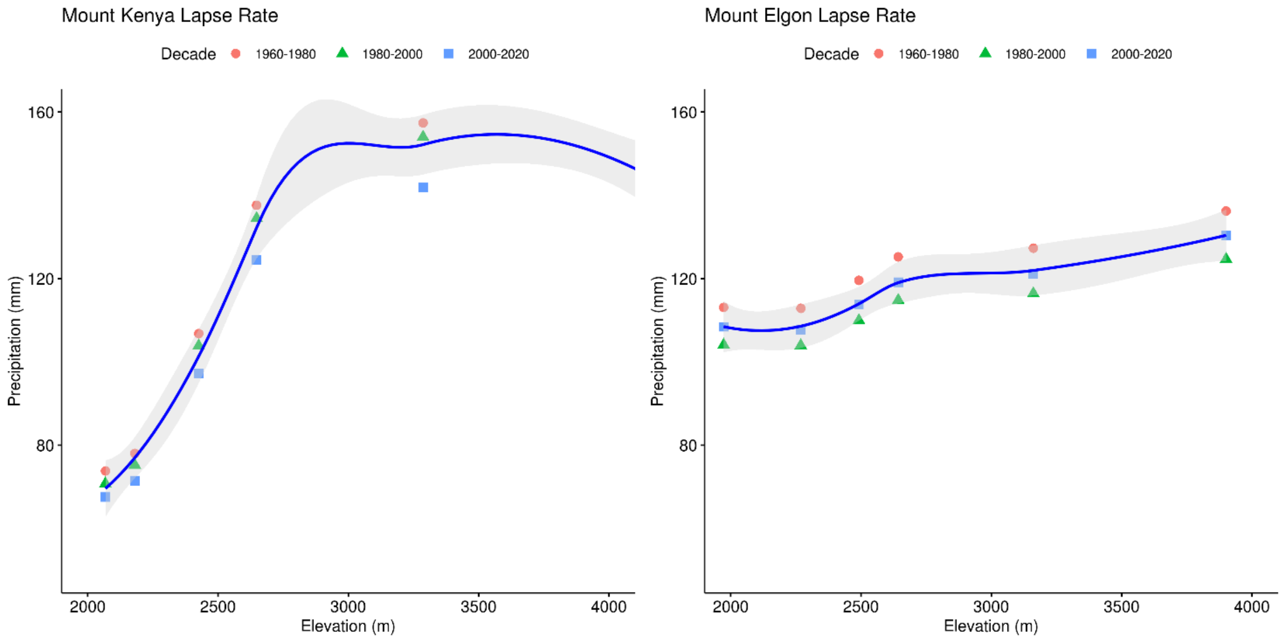

Figure 4-5 Precipitation lapse rate on the western slope of Mount Kenya and the southeast slope of Mount Elgon according to TerraClimate

4.2.2 Ground station data- western slope of Mount Kenya

4.2.2.1 Temperature trends

The ground station data on Mount Kenya displays much different trends than the satellite data, although it only goes back as far as 1992. All three stations on the west side of Mount Kenya (Munyaka at 2070 m, Gate Station at 2420 m, and Met Station at 3050 m) show decreasing mean, minimum, and maximum temperatures since 1992 (MK $p<0.01$) (Figure 4-6;Table 4-2). The only exception is Munyaka minimum temperatures which exhibit a slight increase according to the Mann-kendall test, however the Sen's slope is zero and the KPSS test concludes the time series is stationary (Table 4-2). All of the NRM3 stations were upgraded in 2008, and in 2018 the Munyaka station was changed again after the previous one was damaged (CETRAD, Pers. Comm, 2023). Because of these changes, the data display some strange artefacts and are not reliable for trend analyses (for more detail see Appendix A1). The TerraClimate data at Met Station, on the other hand, displays a monotonic increase since 1958 (Figure 4-7), and a regression line of the departures from the baseline (1961-1990) suggests an increase of 0.024 °C/ year. While the TerraClimate data reads slightly warmer mean temperatures than the ground station and in-situ logger data at Met Station (Appendix A1), the consistency of the data, makes it overall acceptable (see Discussion 4.3.1).

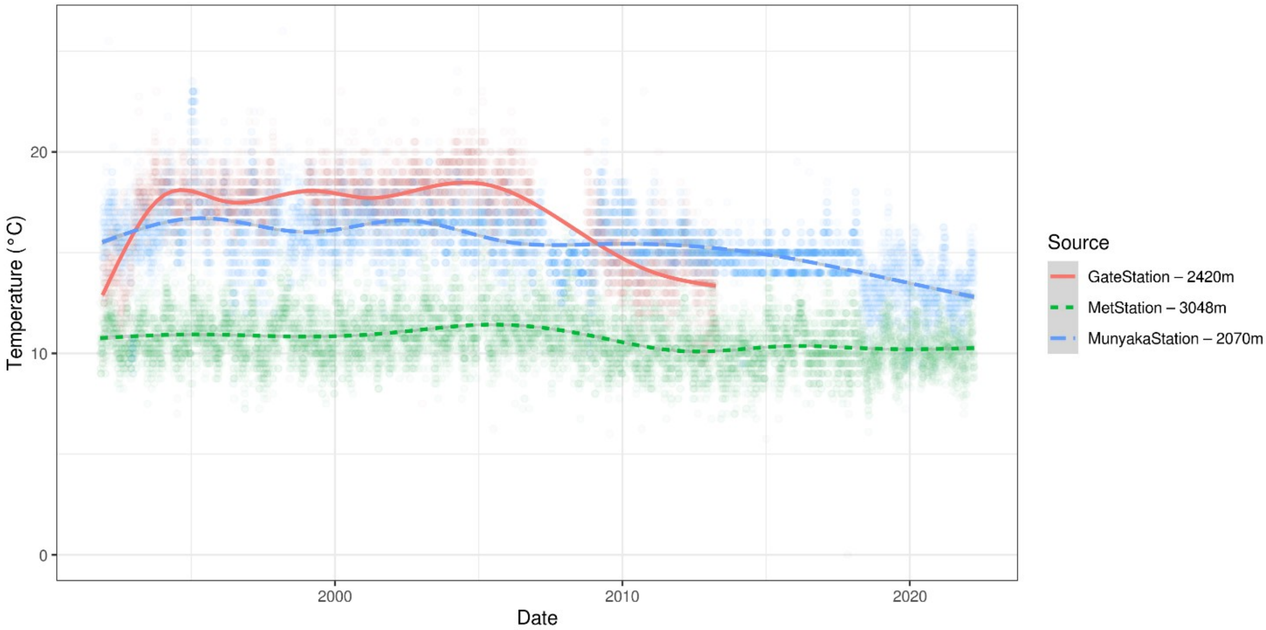

Figure 4-6 Temperature trends for three ground meteorological stations on the western slope of Mount Kenya

Table 4-2 Temperature trends for meteorological stations on Mount Kenya: Met Station, Gate Station, and Munyaka Station

STATION*/ PARAMETER		**Mann-Kendall trend test (2-sided) (Null= No Trend)**	**Seasonal Mann-Kendall trend test (Null= No Seasonal Trend)**	**KPSS Test for Level Stationarity (Null= Stationary)**	**Sen's Slope (Slope/Direction of Trend)**
Met Station	Mean:	-7.39 (p<0.01)	-8.67 (p<0.01)	2.11 (p=0.01)	-0.0027 (p<0.01)
	Max:	-6.11 (p<0.01)	-7.48 (p<0.01)	1.88 (p=0.01)	-0.0041 (p<0.01)
	Min:	-3.61 (p<0.01)	-3.78 (p<0.01)	0.80 (p=0.01)	0.0 (p<0.01)
Gate Station	Mean:	-6.77 (p<0.01)	-6.47 (p<0.01)	1.6213 (p=0.01)	-0.0098 (p<0.01)
	Max:	-6.97 (p<0.01)	-6.83 (p<0.01)	1.79 (p=0.01)	-0.0107 (p<0.01)
	Min:	-7.78 (p<0.01)	-7.54 (p<0.01)	1.14 (p=0.01)	-0.0109 (p<0.01)
Munyaka	Mean:	-14.35 (p<0.01)	-14.30 (p<0.01)	3.6482 (p=0.01)	-0.0084 (p<0.01)
	Max:	-15.08 (p<0.01)	-15.46 (p<0.01)	4.44 (p=0.01)	-0.0189 (p<0.01)
	Min:	2.51 (p=0.01)	2.65 (p<0.01)	0.36 (p=0.09)	0.0 (p=0.01)

**Met Station (3050m); Gate Station (2420m); Munyaka Station (2070m)*

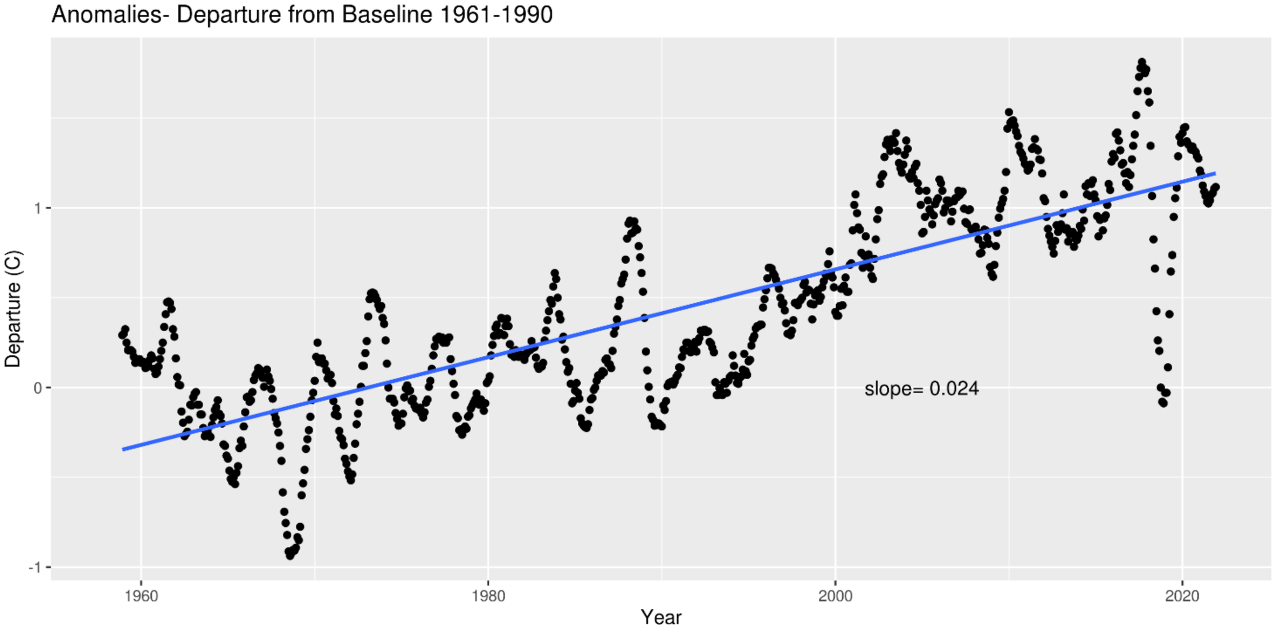

Figure 4-7 TerraClimate trend at Met Station, displayed as departures from a baseline (1961-1990- mean 11.09°C)

4.2.2.2 Monthly temperature patterns

The temperature at Met Station does not vary much during the year, according to the ground station data (Figure 4-8). Temperatures are slightly higher during the dry season months in January- March, but for the most part mean temperatures are within a fairly narrow range of 10- 11 °C throughout the year. The variability each month also is fairly constant, with an inter-quartile range of roughly 1 °C.

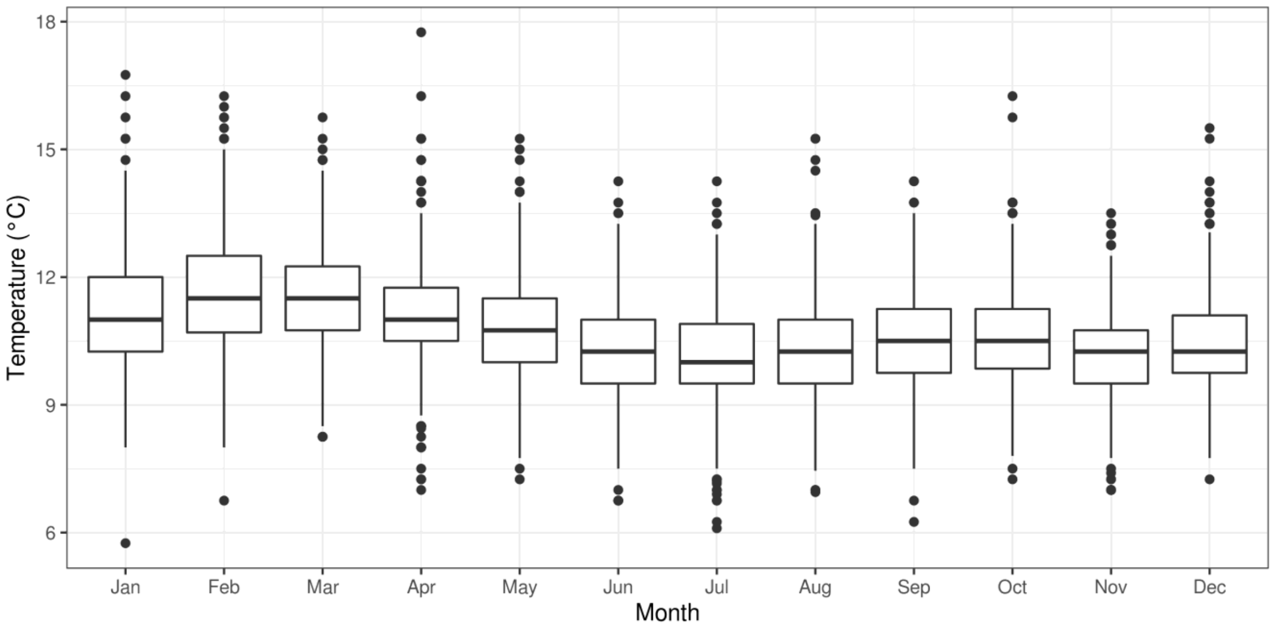

Figure 4-8 Boxplot of temperatures by month at the Naro Moru Meteorological Station since 1991

4.2.2.3 Precipitation trends

The NRM3 meteorological stations going up the west side of the mountain all show no significant trends in precipitation (Table 4-3). Precipitation varies according to elevation, increasing with elevation until Met Station, and then decreasing again for the Teleki station (Figure 4-9). The lower elevation Forest Service weather stations, on the other hand, generally show declining precipitation over the time series. Kabaru, Naro Moru, and Naro Moru FG all have significant negative precipitation trends (MK $p<0.05$; Sen's slopes ranging from -0.02 to -0.05), while Hombe and Nanyuki have significant negative trends when you take into account seasonality (SMK $p<0.05$) (Table 4-3). Nonetheless the trends are slight, and in fact Naro Moru is the only one for which the series can be said to be non-stationary according to the KPSS test.

Table 4-3 Precipitation trends for meteorological stations around Mount Kenya

TYPE	NAME	Mann-Kendall trend test	Seasonal Mann-Kendall trend test	KPSS Test for Level Stationarity+	Sen's Slope
Forest Station	Ragati- 2030m (1957- 2007)	-0.30 (p=0.76)	-0.08 (p=0.94)	0.33 (p=0.10)	-0.0064 (p=0.76)
	Hombe- 1991m (1957- 2007)	-1.94 (p=0.05)	**-3.33 (p<0.01)**	0.34 (p=0.10)	-0.0224 (p=0.05)
	Kabaru- 2237m (1959- 2007)	**-2.02 (p=0.04)**	**-3.37 (p<0.01)**	0.40 (p=0.08)	**-0.0243 (p=0.04)**
	Naro Moru- 2364m (1965- 2003)	**-2.79 (p<0.01)**	**-3.38 (p<0.01)**	**0.52 (p=0.04)**	**-0.0514 (p<0.01)**
	Naro Moru FG- 2195m (1957- 1995)	**-2.09 (p=0.04)**	**-2.00 (p=0.05)**	0.38 (p=0.09)	**-0.0429 (p=0.04)**
	Gathiuru- 2330m (1959- 2004)	-0.95 (p=0.34)	-1.34 (p=0.18)	0.29 (p=0.10)	-0.0126 (p=0.34)
	Nanyuki- 2337m (1989- 2004)	-1.63 (p=0.10)	**-2.44 (p=0.01)**	0.36 (p=0.09)	-0.1140 (p=0.10)
NRM3 Stations	Munyaka- 2070m (1991- 2020)	-0.72 (p=0.47)	-0.51 (p=0.61)	0.07 (p=0.10)	-0.0130 (p=0.47)
	Gate Station- 2420m (1968- 2012)	-0.94 (p=0.35)	-0.81 (p=0.42)	0.05 (p=0.10)	-0.0150 (p=0.35)
	Met Station- 3050m (1978- 2020)	-0.11 (p=0.91)	-0.18 (p=0.86)	0.03 (p=0.10)	-0.0026 (p=0.91)
	Moorland- 3771m (1990- 1995)	-0.47 (p=0.64)	-1.14 (p=0.25)	0.20 (p=0.10)	-0.1118 (p=0.64)
	Teleki- 4262m (1978- 2002)	-1.01 (p=0.31)	-1.00 (p=0.32)	0.16 (p=0.10)	-0.0324 (p=0.31)

+Only KPSS results are reported here. ADF test continues to show sometimes conflicting results

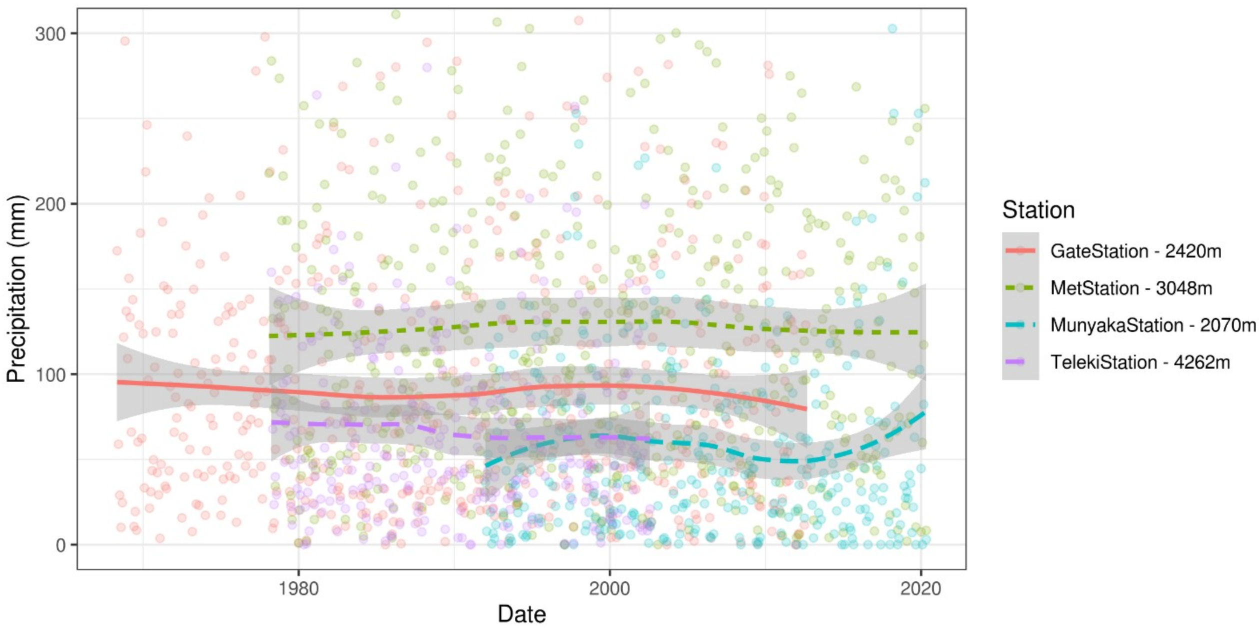

Figure 4-9 Precipitation trends for NRM3 meteorological stations on Mount Kenya. Coloured line displays Lowess line with 95% confidence intervals

4.2.2.4 Seasonal precipitation patterns

There is a bimodal rainfall pattern on the mountain, with the primary wet seasons in March - May (MAM) and September - November (SON). This pattern is most pronounced in the higher elevation stations – Met Station and Gate Station - where monthly rainfall exceeds 200 mm during the rainy months and less than 100 mm during the dry months (Figure 4-10). However, there is considerable variability in the rainy season months. Looking at the month of April, for example, the range of values at Met Station goes from 45 mm to almost 476 mm.

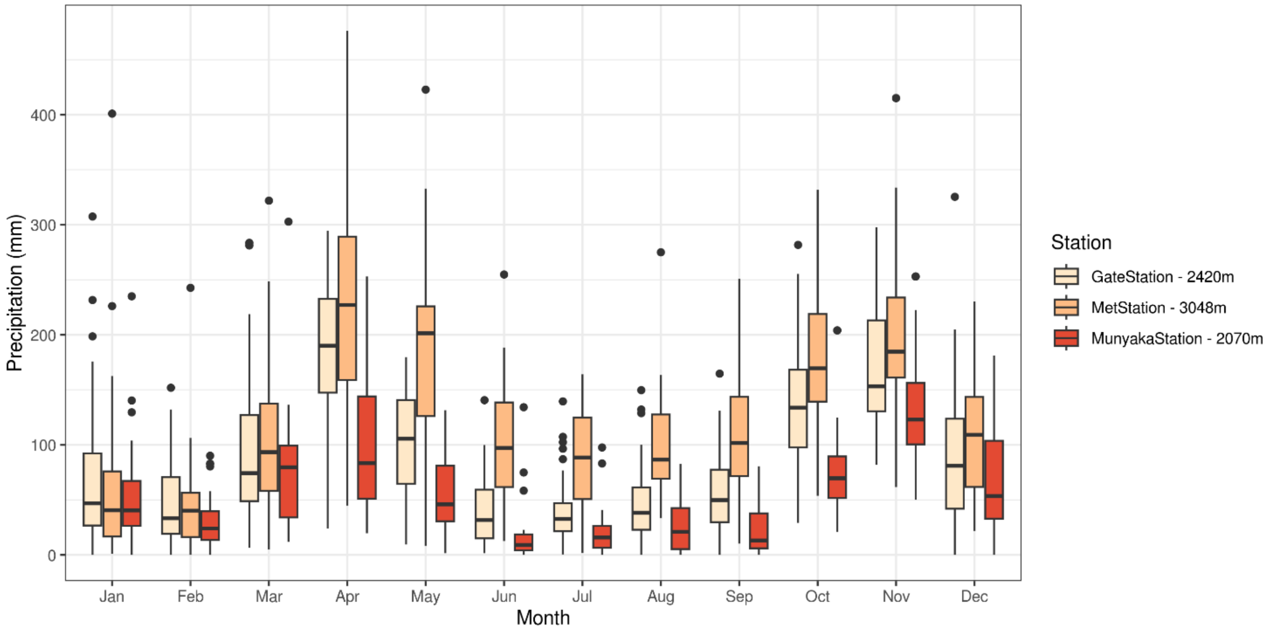

Figure 4-10 Boxplot of monthly precipitation for NRM3 meteorological stations going up the western slope of Mount Kenya

At Met Station, monthly precipitation overall has not changed much between 1980- 2000 and 2000 - 2020, but precipitation is noticeably lower during the dry season months of January, February, July, and August (Figure 4-11). When precipitation is broken down into 3 month seasons, this decline in dry season temperature is not significant (p=0.31 for DJF and p=0.68 for JJA), however Munyaka Station does shows decreasing DJF (long dry season) rainfall over time (p=0.01). Among the Forest Service stations, Hombe and Nanyuki also show significant declines in the second dry season – JJA (p=0.02 for Hombe, and p<0.01 for Nanyuki) (Table 4-4).

Table 4-4 Trends in seasonal precipitation around Mount Kenya

Type	Station	Season	Slope	P value
NRM3 Stations	Gate Station- 2420m (1968- 2012)	DJF	-0.53	0.68
		MAM	0.42	0.76
		JJA	-0.51	0.48
		SON	-0.93	0.43
	Met Station- 3050m (1978- 2020)	DJF	-1.44	0.31
		MAM	-0.28	0.89
		JJA	0.50	0.68
		SON	1.21	0.41
	Munyaka- 2070m (1991- 2020)	DJF	**-3.81**	**0.01**
		MAM	0.94	0.73
		JJA	-0.02	0.99
		SON	2.45	0.20
Forest Stations	Hombe- 1991m (1957- 2007)	DJF	-0.80	0.38
		MAM	-1.53	0.28
		JJA	**-0.73**	**0.02**
		SON	-2.46	0.24
	Kabaru- 2237m (1959- 2007)	DJF	-1.20	0.26
		MAM	-2.04	0.12
		JJA	**-1.08**	**<0.01**
		SON	-2.55	0.15

** Shown are significant seasonal trends for the linear regression of seasonal precipitation over time at $p<0.05$ level. DJF= Dec-Jan-Feb; MAM= Mar-Apr-May;JJA=Jun-Jul-Aug;SON=Sep-Oct-Nov*

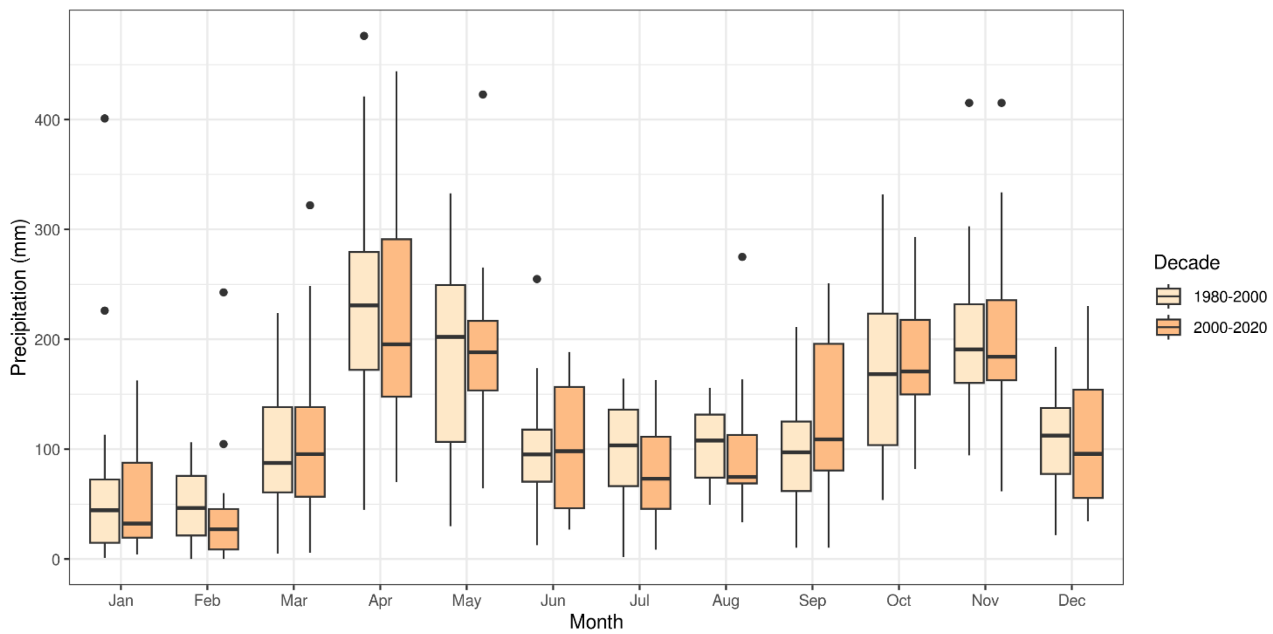

Figure 4-11 Boxplot of monthly precipitation at Naro Moru Met Station (3048 m) by decade

4.2.3 Streamflow data

4.2.3.1 Discharge trends at the base of the two mountains

The Water Resources Authority (WRA) data for the stations surrounding the two mountains is quite spotty, with plenty of data gaps and discontinuous coverage. The six stations around the two mountains, however, all have at least a period of continuous coverage. These six stations display considerable inter-annual variation in discharge, and the flow around Mount Elgon is much higher than in Mount Kenya (Appendix C1). However looking at average discharge, 4 of the 6 stations show significant declines over time: Muhuhi (MK $p<0.01$; SS -0.0004), Lower Sagana (MK $p<0.01$; SS -0.0002), Malakisi (MK $p<0.01$; SS -0.0020), and Koitobos (MK $p<0.01$; SS -0.0012) (Table 4-5). Rongai with the longest record, however, shows no significant trend (MK $p=0.27$).

Table 4-5 Trends in mean discharge for stations downstream of Teleki and Koitobos valleys

Station	**Mann-Kendall Test (2-sided)**	**Seasonal Mann-Kendall trend test**	**KPSS Test for Level Stationarity**	**Sens Slope**
MOUNT KENYA				
4BB03- Muhuhi (1981-2002)	**-4.88 (p<0.01)**	**-5.86 (p<0.01)**	0.26 (p=0.10)	**-0.0004 (p<0.01)**
5BC05- Rongai (1948-2019)	1.10 (p=0.27)	1.32 (p=0.19)	0.48 (p=0.05)	0.0000 (p=0.27)
4AA06- Lower Sagana (1960-1992)	**-10.38 (p<0.01)**	**-12.28 (p<0.01)**	**1.60 (p=0.01)**	**-0.0002 (p<0.01)**
MOUNT ELGON				
1AB01- Malakisi (1978-2019)	**-2.88 (p<0.01)**	**-3.10 (p<0.01)**	**0.59 (p=0.02)**	**-0.0020 (p<0.01)**
1BE06- Koitobos (1948-2003)	**-3.67 (<0.01)**	**-3.92 (p<0.01)**	**1.26 (p=0.01)**	**-0.0012 (p<0.01)**
1DB03- Kuywa (1978-1997)	-0.15 (p=0.88)	0.10 (p=0.92)	0.10 (p=0.10)	0.0000 (p=0.88)

**Kenya Water Resources Authority (WRA)*

4.2.3.2 Discharge trends- western slope of Mount Kenya

The five NRM3 gauging stations on the western slope of Mount Kenya provide a more detailed look at discharge patterns. Although these have only been running for 30 years (1985-2015), there are less data gaps and the temporal resolution is better - twice a day. All show significant declines in discharge over the 30 year period of record (MK $p<0.05$), with the exception of the A5 station, which shows no trend (MK $p=0.77$, $p=0.06$, $p=0.19$ for max, min, and mean discharge respectively), and A3, which only shows declines in minimum flow (MK $p<0.01$) (Table 4-6). Generally, the decline is greater for maximum flows (Sen's Slopes ranging from -0.0013 to -0.0023) than minimum or average flows (SS -0.0002 to -0.0006).

The seasonal patterns of the Naro Moru and Burguret rivers generally follows precipitation patterns, with highest discharges in April, May, and November (Figure 4-12). The stations further down have higher average discharges due to the larger contributing area at that point. Nevertheless there is also substantial abstraction of water that occurs along these rivers which dampens the flow, and there have been some months were the minimum flow is zero even down at A5 and A6 (Aeschbacher et al., 2005).

Table 4-6 Ground station discharge trends for NRM3 stations on Mount Kenya (1985- 2015)

Station	**Type**	**Mann-Kendall trend test**	**Seasonal Mann-Kendall trend test**	**KPSS Test for Stationarity**	**Sen's Slope**
A3- Naro Moru Forest (N) (40sq km)*	Max	0.43 (p=0.66)	0.71 (p=0.48)	**0.63 (p=0.02)**	0.0003 (p=0.66)
	Min	**-6.21 (p<0.01)**	**-6.03 (p<0.01)**	**0.96 (p=0.01)**	**-0.0004 (p<0.01)**
	Avg	-1.64 (p=0.10)	-1.69 (p=0.09)	0.15 (p=0.10)	-0.0003 (p=0.10)
A4- N.M. Forest (S) (23 sq km)	Max	**-6.87 (p<0.01)**	**-7.56 (p<0.01)**	**2.10 (p=0.01)**	**-0.0023 (p<0.01)**
	Min	**-7.54 (p<0.01)**	**-7.63 (p<0.01)**	**0.69 (p=0.01)**	**-0.0003 (p<0.01)**
	Avg	**-6.82 (p<0.01)**	**-7.41 (p<0.01)**	**1.30 (p=0.01)**	-0.0008 **(p<0.01)**
A5- N.M. Footzone (63 sq km)	Max	0.29 (p=0.77)	0.26 (p=0.80)	0.08 (p=0.10)	0.0003 (p=0.77)
	Min	1.94 (p=0.05)	**2.11 (p=0.03)**	0.12 (p=0.10)	0.0002 (p=0.05)
	Avg	1.31 (p=0.19)	1.48 (p=0.14)	0.10 (p=0.10)	0.0004 (p=0.19)
A6- N.M. Savannah (174 sq km)	Max	**-2.60 (p<0.01)**	**-2.69 (p<0.01)**	**0.54 (p=0.03)**	**-0.0022 (<0.01)**
	Min	**-6.36 (p<0.01)**	**-6.33 (p<0.01)**	**0.62 (p=0.02)**	**-0.0002 (p<0.01)**
	Avg	**-2.97 (p<0.01)**	**-3.32 (p<0.01)**	0.34 (p=0.10)	**-0.0006 (p<0.01)**
A8- Burguret (99 sq km)	Max	**-2.40 (p=0.02)**	**-3.33 (p<0.01)**	**0.51 (p=0.04)**	**-0.0013 (p=0.02)**
	Min	**-6.66 (p<0.01)**	**-7.69 (p<0.01)**	**1.00 (p=0.01)**	**-0.0006 (p<0.01)**
	Avg	**-3.15 (p<0.01)**	**-4.31 (p<0.01)**	**0.47 (p=0.05)**	**-0.0006 (p<0.01)**

** Drainage area for the watershed above the gauge*

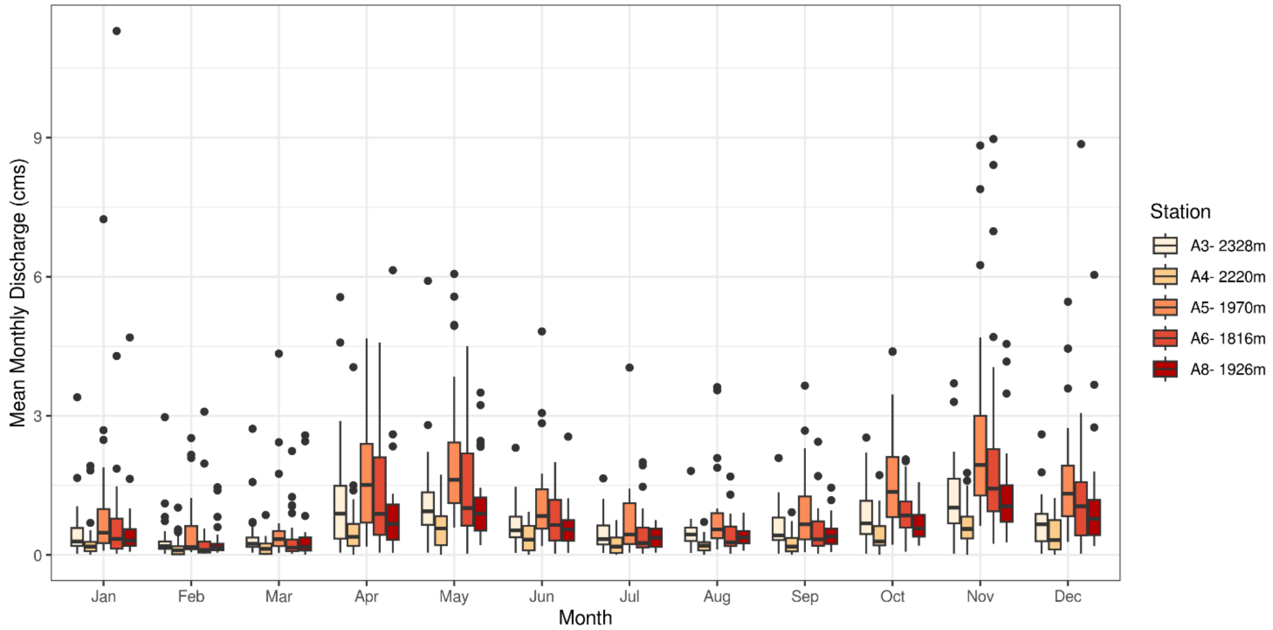

Figure 4-12 Boxplot of monthly discharge for NRM3 gauge stations on the western slope of Mount Kenya

4.2.3.3 Discharge patterns for the A3 gauge

The A3 gauge is the highest one up in the mountain and is thus least affected by land-use changes and water abstractions; it is, therefore, the one that can best reveal direct impacts of climate change. The gauge is located directly downstream from the Teleki Valley and the other NRM3 ground stations (Figure 4-13). The A3 basin ranges from 5080 m to 2298 m, the average slope is 31%, and the runoff curve number is 66 (Notter, 2003). Curve numbers range from 1 to 100 with 100 being 100% runoff; numbers in the 60s are typical of natural ecosystems with decently drained soils (NRCS, 1986).

Baseflow (minimum flow) discharge for the A3 station is low- generally less than 0.25 cubic meters per second (cms) and only occasionally reaching above 1 cms, and the trend is slightly decreasing over time (MK $p<0.01$, SS=-0.0004) (Table 4-6). However an analysis of anomalies in the data shows an exceptional amount of high peak flows since 2005 (Figure 4-14). The absolute value of these peak flows (>30cms) is likely not accurate, as the rating curve used by the NRM3 team is generally only accurate for flows up to 8 cubic meters per second (Notter, 2003), but the relative values still show the existence of more extreme flows in the last decade.

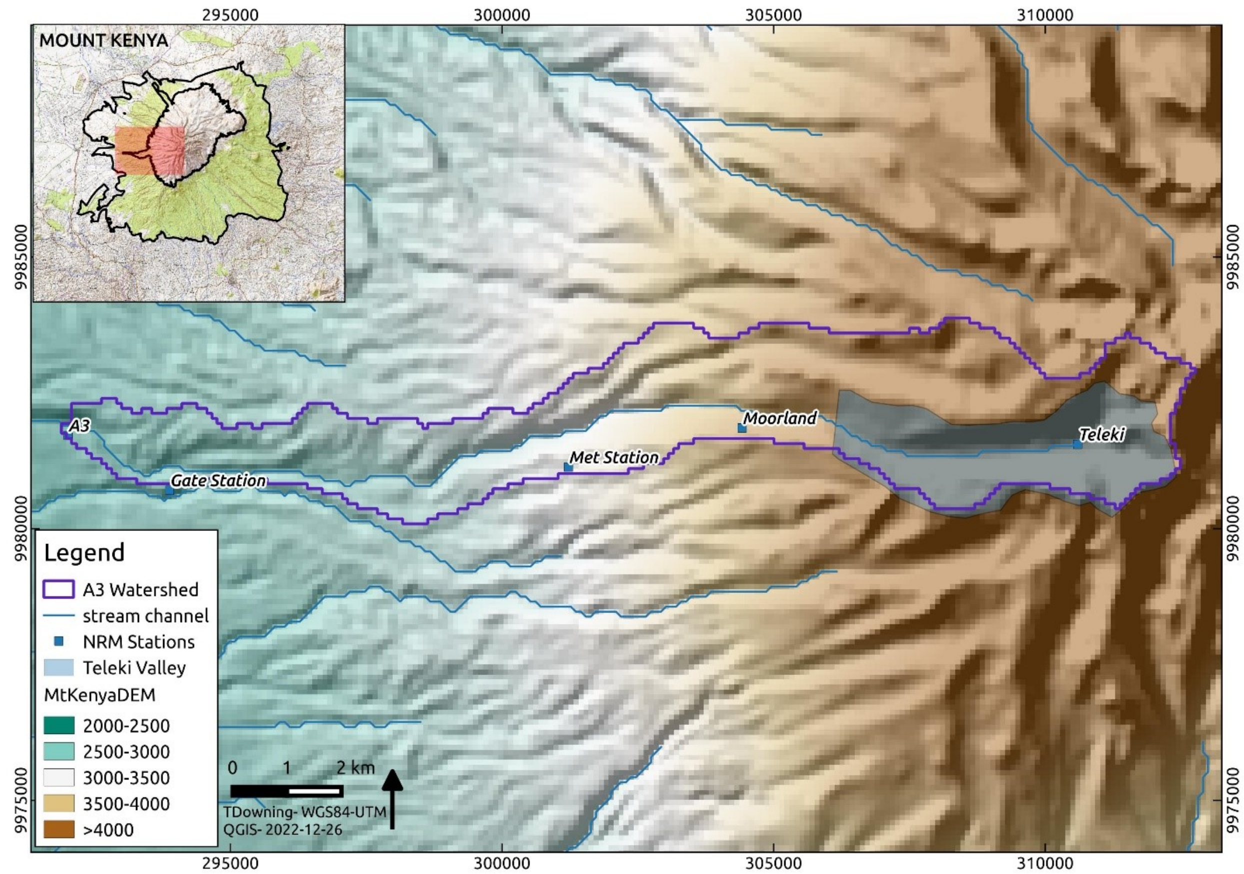

Figure 4-13 Drainage basin for the A3 stream gauge below Teleki Valley, Mount Kenya

The flood frequency analysis for A3 from 1985-2015 shows that a major flood has a recurrence interval of about 5 years (Figure 4-15- again looking just at relative flood size, as the absolute size is questionable). However, if the last decade (2005 – 2015) is removed from the series - looking just at the period 1985-2005 - then that same magnitude flood is now a 20 or 30 year event (Figure 4-16). This suggests a high volatility in stream flow in the last decade.

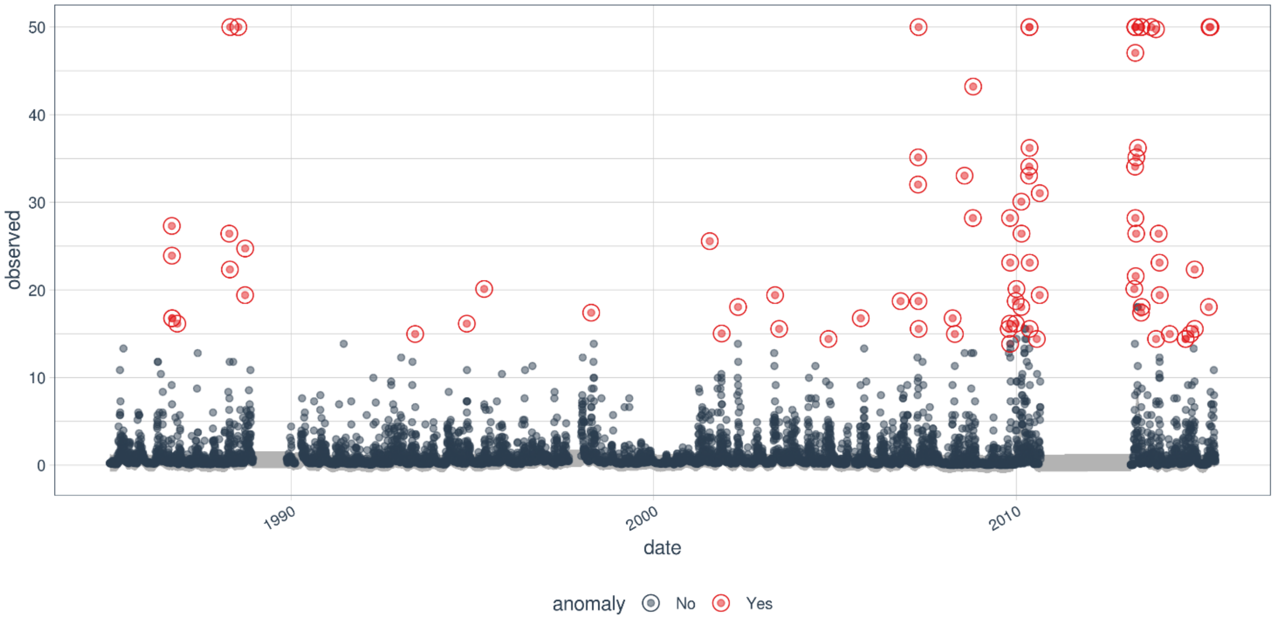

Figure 4-14 Raw discharge and possible anomalies at the A3 gauge on Mount Kenya since 1985

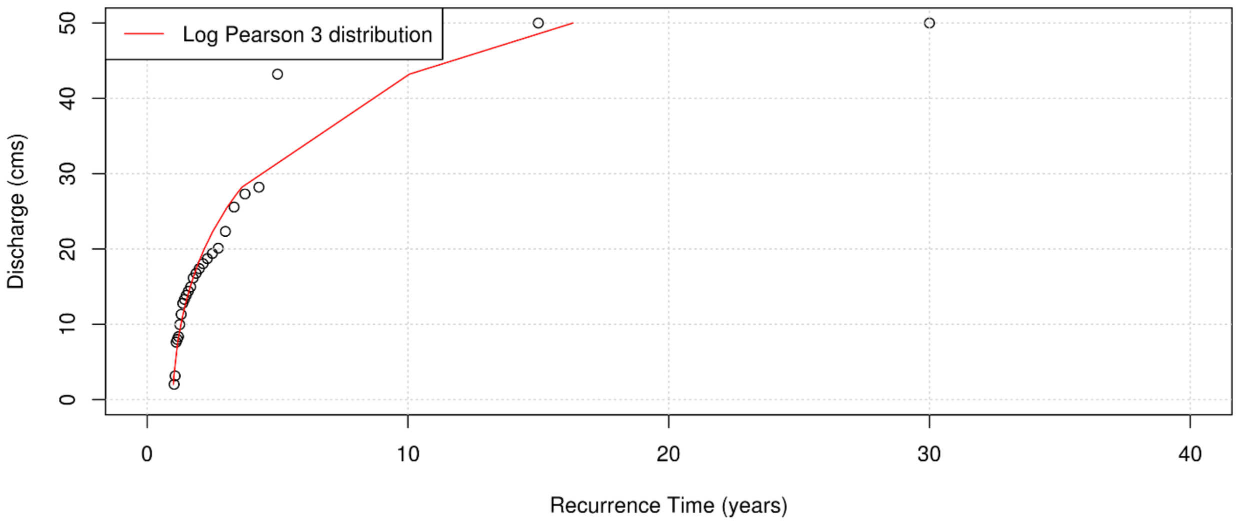

Figure 4-15 Storm recurrence interval for the A3 gauge for the entire period of record- 1985-2015

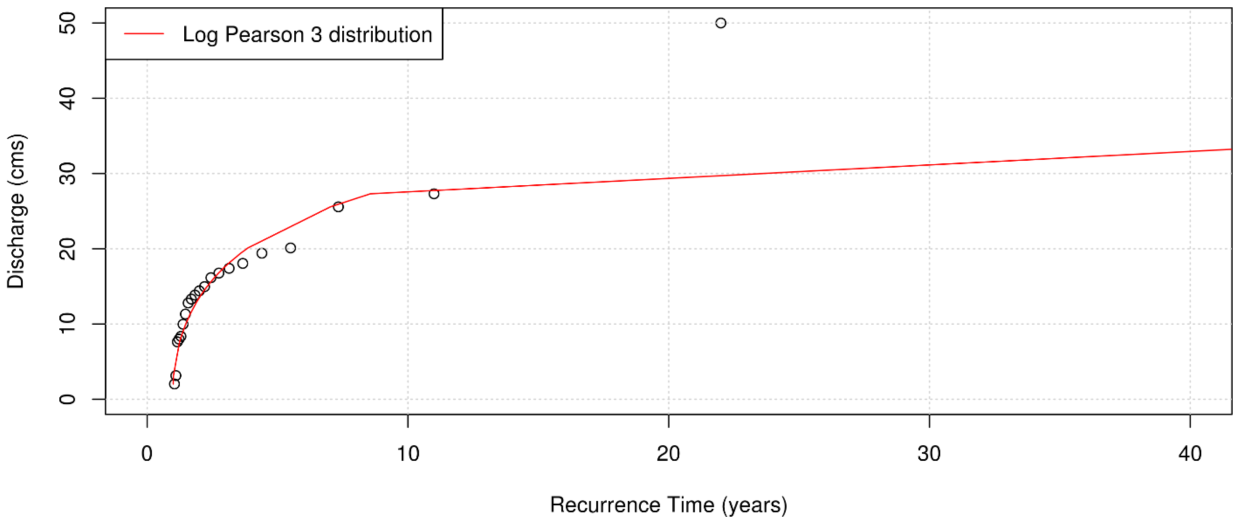

Figure 4-16 Storm recurrence interval for the A3 gauge for 1985-2005

4.2.4 In-situ data- Mount Kenya and Mount Elgon

4.2.4.1 Temperature lapse rates from in-situ data loggers

The lapse rate from the in-situ data (3200 m to 4200 m) shows higher values than the TerraClimate estimates, although again Mount Elgon has the steeper lapse rate -0.7 °C/100 m versus 0.61 °C/100 m on Mount Kenya (Figure 4-17). Overall Mount Elgon was warmer than Mount Kenya - at least 1 °C degree warmer at each elevation – but absolute minimum temperatures were also lower in Mount Elgon, and there were correspondingly more frost days (Table 4-7). The 4200 m logger (4100 m for Mount Elgon) was anomalous in both mountains. This logger was placed among rocks in both mountains as there was very little shade available, and this likely caused excess radiation warming from the rocks (Appendix C1; Appendix B1). Therefore, this data was not included in the analysis.

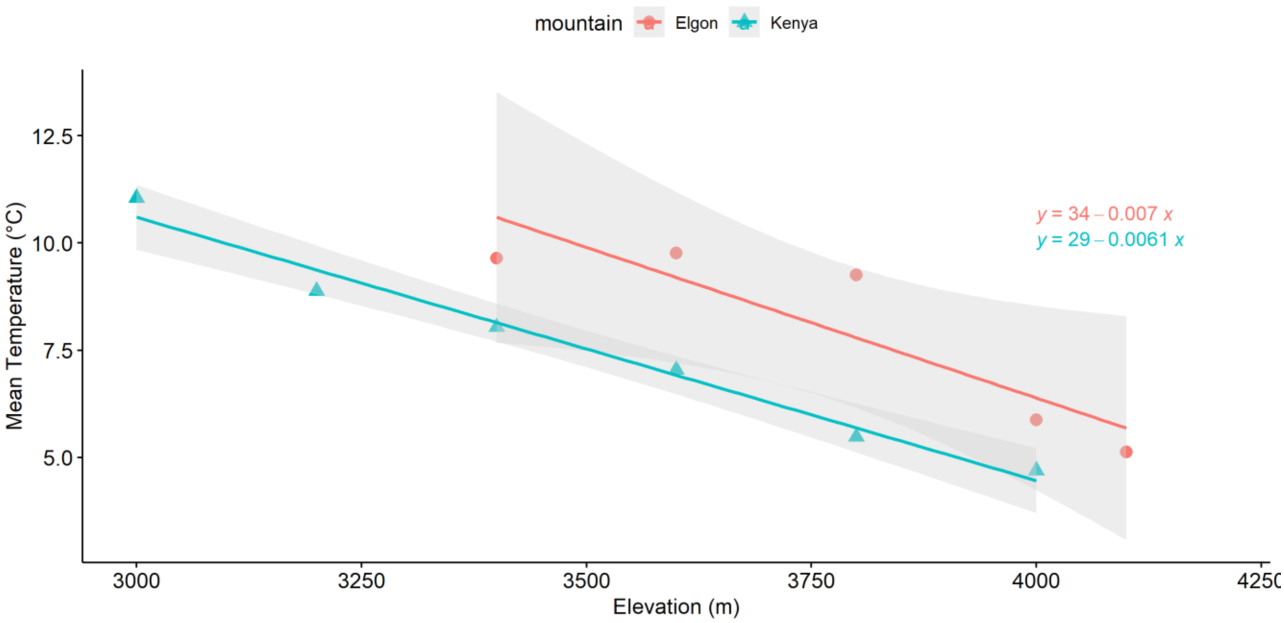

Figure 4-17 Mean temperature lapse rate in Mount Elgon and Mount Kenya from data loggers between 3000 and 4100 m.a.s.l. The coloured lines show the least squares regression line with 95% confidence intervals

Table 4-7 Temperature statistics for Mount Kenya and Mount Elgon by elevation (Sept - Feb#)

Elevation (m)	**Mean mean (°C)**		**Abs. Min (°C)**		**Abs. Max (°C)**		**No. of Frost Days (% frost days)**	
	Kenya	Elgon	Kenya	Elgon	Kenya	Elgon	Kenya	Elgon
3200*	8.88		3.60		22.73			
3400	8.04	9.64	-0.43	2.14	26.17	22.43	4 (3%)	0 (0%)
3600	7.04	9.76	-0.69	-1.38	23.38	35.03	7 (5%)	3 (2%)
3800	5.48	9.25	-1.68	-3.61	22.09	45.56	19 (12%)	43 (28%)
4000	4.69	5.87	-1.55	-4.21	14.45	30.89	21 (14%)	71 (46%)
4200+	5.07	5.13	-0.17	-2.45	19.77	25.09	1 (1%)	54 (35%)

 # Sept. 8, 2021 to Feb. 8, 2022 for Mt. Elgon (154 days) and Sept. 21, 2021 to Feb. 22, 2022 for Mt. Kenya (155 days)
** For Mt. Elgon, the 3200 logger was never recovered.*
+For Mt. Elgon this logger was placed at 4100 m

4.2.4.2 Daily and monthly temperature patterns

Temperature in the alpine zone of both mountains had high diurnal variation but low seasonal variation. The 4000 m Mount Kenya data logger was a typical example. The temperatures over the course of a day exhibited a distinct parabolic shape, with lowest temperatures around 2 am and hottest temperatures around 12 pm (Figure 4-18). The temperature warmed rapidly from an average of 1.7 °C at 6 am to 9.0 °C by 10 am, and most of this warming happened within just a half-hour time span. On November 7th, 2022 the temperature warmed by 10.4 °C just between 7 am and 7:30

am (Figure 4-19). The hottest part of the day then was around 10:30 am, after which it would start to cool down, at a slower rate than in the morning.

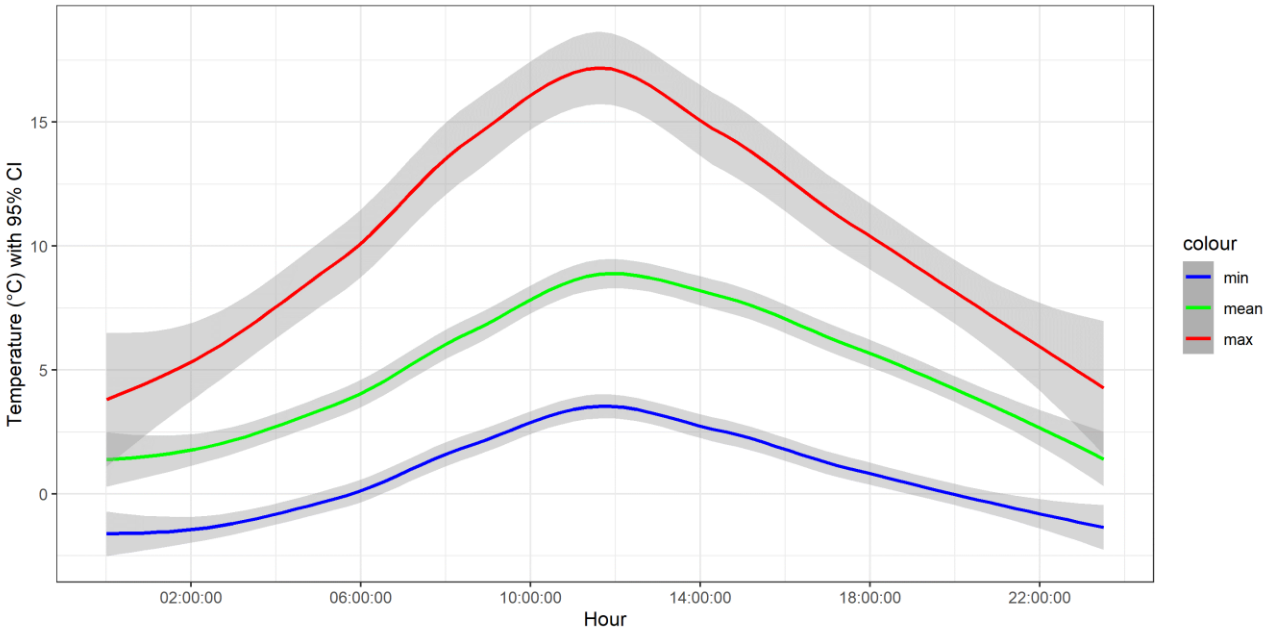

Figure 4-18 Diurnal mean, minimum, and maximum temperatures with 95% confidence intervals at the 4000 m.a.s.l. logger on Mount Kenya

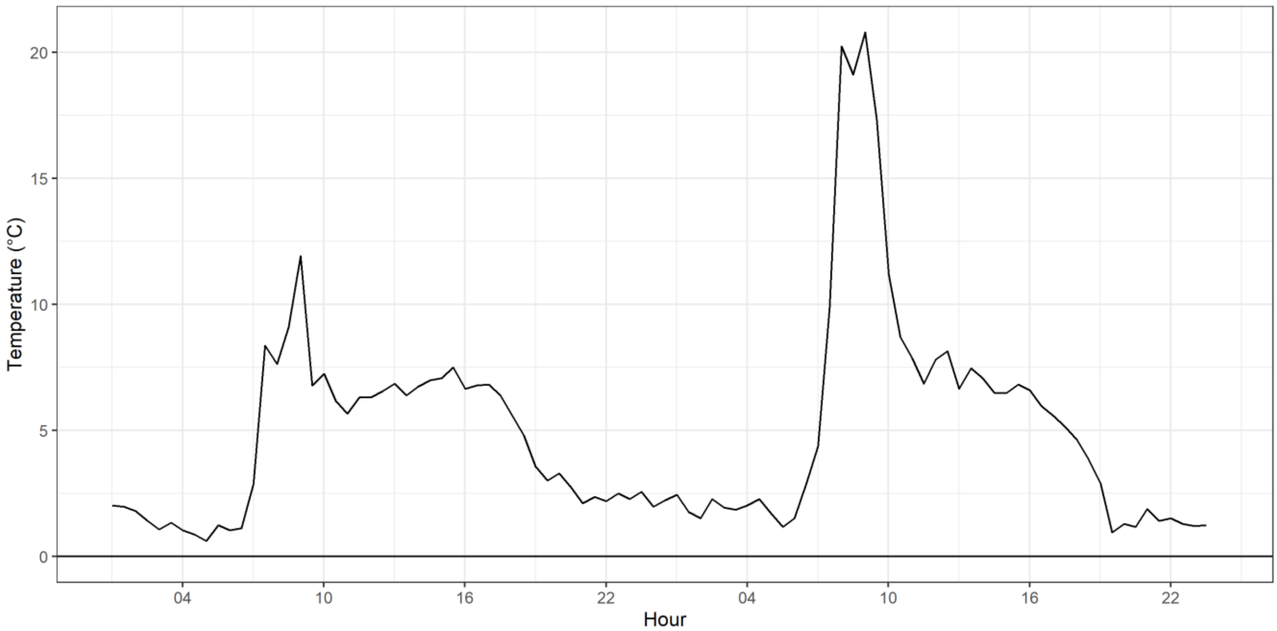

Figure 4-19 Raw data for temperatures on November 6-7 at 4000 m.a.s.l. logger on Mount Kenya. Logger recorded at 30 minute intervals

The mean daily range was 9.79 °C (or 7.29 °C if calculated as the difference between coldest and warmest hours), while the mean monthly range (difference between the coldest and warmest months) over the course of the year was just 1.67 °C (Table 4-8). Thus there was much more temperature variability by day than there was by month. There were 88 frost days (21%) where temperature dropped below freezing. Overall, the coldest month according to mean temperature was November (4.30 °C), corresponding to the short rains. The hottest month was March (5.97 °C) - the long dry season. Overall the mean temperature was 4.90 °C at 4000 m, with an absolute minimum of -1.68 °C and absolute maximum of 20.80 °C (Table 4-8).

Table 4-8 Temperature statistics at 4000 m.a.s.l - Teleki Valley (September 2021-November- 2022)

Statistic	**Value (°C)**	**Statistic**	**Value**
Absolute Minimum	-1.68	Coldest month (mean)	November
Absolute Maximum	20.80	Hottest month (mean)	March
Mean of Daily Means	4.90	Coldest Hour (mean)	6:00am
Mean Daily Range	9.79	Hottest Hour (mean)	10:00am
Minimum Daily Range	2.19	Hour with greatest mean range	8:00am
Maximum Daily Range	19.86	Month with greatest mean range	March
Mean difference- coldest and warmest months	1.67	Number of Frost Days	88 (21%)
Mean difference- coldest and warmest hours	7.29	Month with Most Frost Days	October

4.2.4.3 Patterns in soil properties

Soils on the two mountains were humic soils- mostly cambisols and andosols. These were acidic soils with a high level of organic matter, a low bulk density, and a high cation exchange capacity. In low-lying bogs the soils transitioned into histosols with a very thick O horizon. The soils were rich in the base nutrients with base saturation values ranging from 42-97% and a high carbon to nitrogen ratio of 19-28. Overall, the Mount Elgon soils were richer with higher levels of base cations and carbon. Carbon content, in particular, was significantly higher on Mount Elgon ($t(10=2.58$; $p=0.03$). Metals, however, were on the whole lower than in Mount Kenya, particularly iron ($t(10)=-2.24$; $p=0.05$) (Table 4-9).

Table 4-9 Soil properties by mountain (mean across all elevations- 3200 - 4200 m.a.s.l.)

Soil Parameter	Mt. Elgon	Mt. Kenya	Two-tailed t-test p-value
pH	5.26	4.82	0.17
Na (meq%)	0.96	0.58	0.46
K (meq%)	0.64	0.60	0.83
Ca (meq%)	***10.17***	***1.37***	***0.07***
Mg (meq%)	3.01	2.18	0.21
Nitrogen %	***0.60***	***0.47***	***0.08***
Carbon %	***17.02***	***9.15***	***0.03***
Phosphorus ppm	56.67	48.53	0.33
Copper ppm	0.44	0.70	0.31
Iron ppm	***22.00***	***104.42***	***0.05***
Zinc ppm	7.46	12.98	0.34

** Bold values show significance at 90% confidence level*

A Spearman's correlation analysis between soil properties and temperatures shows that temperatures were only weakly correlated with soil properties. Calcium was the only property that was significantly correlated with temperature - correlating positively with mean maximum temperature (meanmax). (Figure 4-20). Other soil properties correlating positively (but not significantly) with temperature were pH, calcium, nitrogen, and carbon; these were all generally more abundant in Mount Elgon, which was overall warmer at each elevation. Soil properties had a weak relationship with elevation. Carbon and nitrogen generally tracked with each other, but did not show any obvious trend with elevation (Figure 4-21); neither did the cations (see Appendix C2).

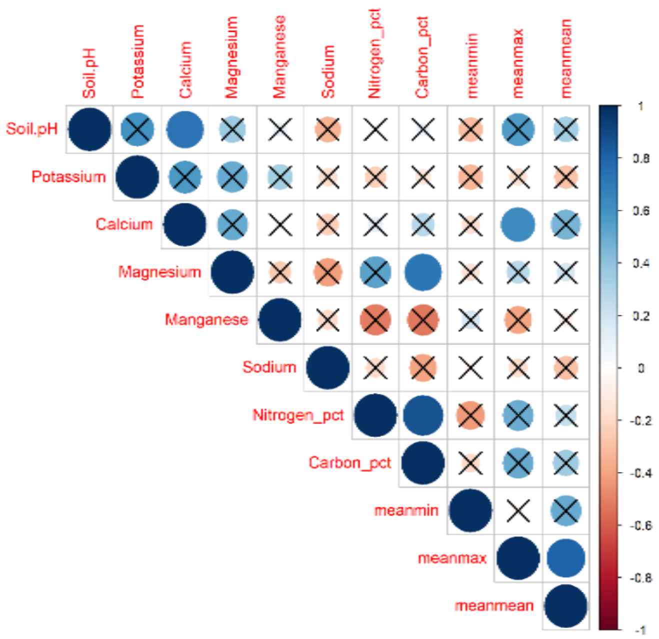

Figure 4-20 Spearman's correlation between soil properties and temperatures

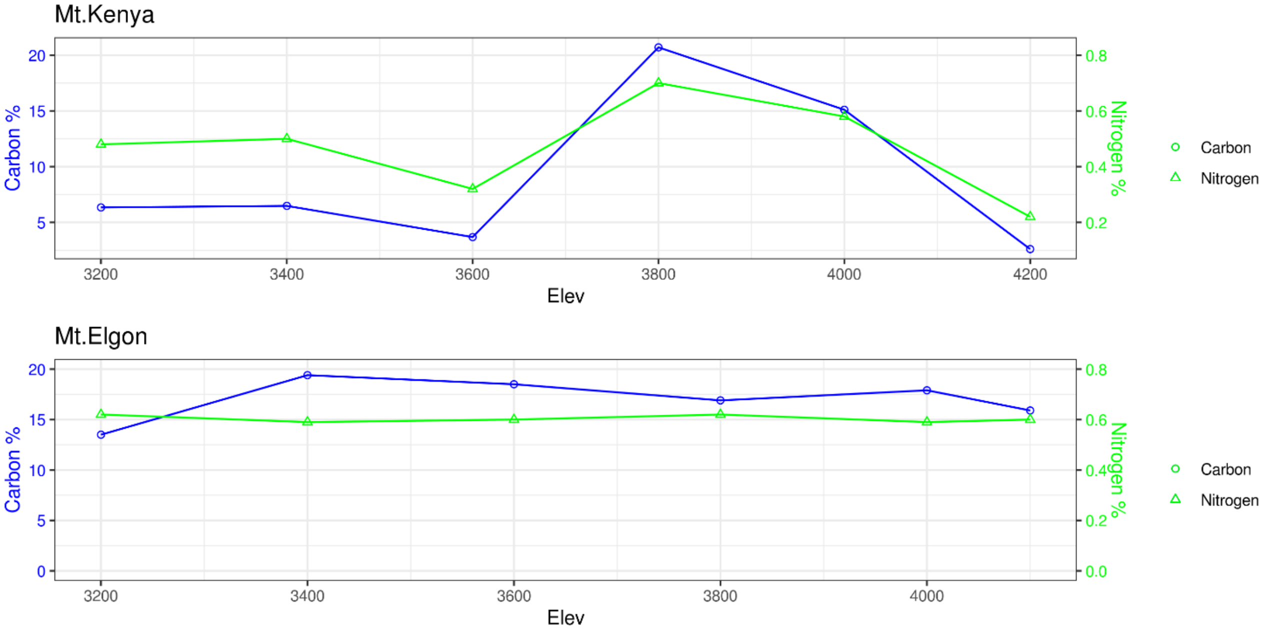

Figure 4-21 Percent carbon and nitrogen in soil by elevation in Mount Elgon and Mount Kenya

Soil properties for both mountains also generally fell within the range of historically reported values for comparable elevations (Appendix C2). The only parameter to be significantly lower was Nitrogen: t(16)=3.65; p<0.01) (Figure 4-22).

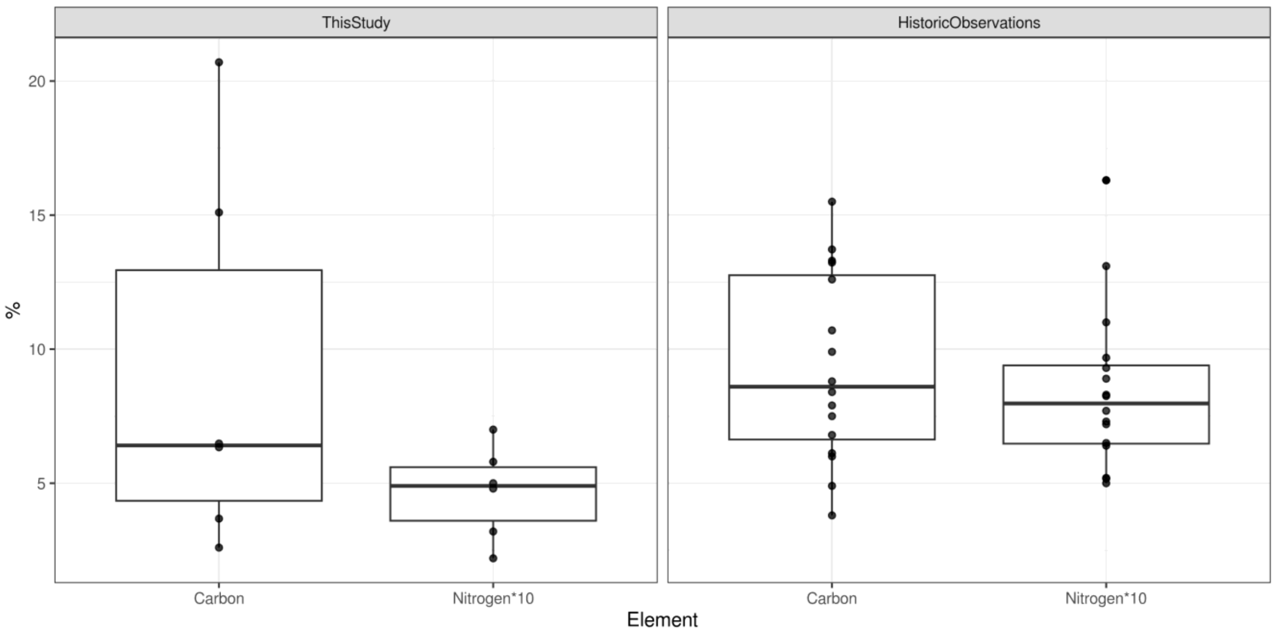

Figure 4-22 Comparison of Carbon and Nitrogen values in this study versus historical studies ranging from 1967 to 1987 (Coe, 1967; Mahaney & Boyer, 1987; Speck, 1982; Young, 1984)

4.2.4.4 Temperature comparisons with historical observations

There are no permanent weather stations for either Koitobos Valley, Mount Elgon, or Teleki Valley, Mount Kenya, but there are historic temperature observations, particularly in Teleki Valley. Mean temperatures in this study generally fell within the range of historical values at comparable elevations (4.7-4.8°C vs. 1.9- 6.7°C), and the same was true for maximum temperatures, with the exception of the data from Grab et al. (2004) which is likely erroneous. The data from Grab et al. (2004) has suspiciously high maximum temperatures, which is likely an artefact of being exposed to direct sunlight and overheating (see Appendix C2). However the absolute minimums were substantially higher in this study (-0.2 to -1.6°C vs. -5 to -6.7°C), leading to correspondingly less frost days (13% vs. 86 - 98%) (Table 4-10). In Mount Elgon too the mean temperature is similar to the historic record (5.9°C vs. 6.1°C), while the absolute maximum is somewhat higher (30.9°C vs. 25.8°C), as is the absolute minimum (-4.2°C vs. -6.0°C). The number of frost days on Mount Elgon are also less: 46% vs. 63% (Table 4-10).

Table 4-10 Hobo temperature logger data as compared to historical records (surface temperature, less than 20cm height)

Author	Elevation (m)	Date	Mean (ºC)	Abs. Max (ºC)	Abs. Min (ºC)	Frost Days %	Duration
Teleki Valley							
Hedberg, 1964	4200	1948	3.1	14	-6	86	one week, Aug
Coe, 1967	4191	1958	1.9	11	-6.7		one month, Dec- Jan
Beck et al., 1981	4066	1979	5.5	18	-5		3 weeks, March
Grab et al., 2004*	4200	1998	6.7	42.8	-7.2	98	6 months, Aug - Dec
Current Study	4000	2021	4.7	14.5	-1.6	13	5 months, Sept - Feb
Current Study+	4200	2021	4.8	19.8	-0.2	<1	5 months, Sept - Feb
Koitobos Valley							
Wesche, 2002#	3750	1997	6.1	25.8	-6.0	63	1 year- Nov- Oct
Current Study	4000	2021	5.9	30.9	-4.2	46	5 months-Sept to Feb

**Max temperature is highly suspect- likely it was placed in direct sunlight resulting in artificially high maximum temperatures*
+4200 m logger was hidden under a rock which may have modified daily temperature extremes
 # Exact location not indicated, but the two main valleys in the study are the Dirigana valley in Uganda and the Koitobos valley in Kenya.
(Beck et al., 1981; Coe, 1967; Grab et al., 2004; Hedberg, 1964; Wesche, 2002)

Lapse rates in this study were largely similar to values reported in the literature. The tropical alpine average lapse rate is said to be 0.6°C/100 m (Rundel, 1994), which is slightly steeper than the moist adiabat that describes the thermodynamic saturation point (Betts, 1982; Loomis et al., 2017). Historically measured values range from 0.44 to 0.68 °C/100 m (Table 4-11).

Table 4-11 Lapse rates for Mount Kenya and Mount Elgon

Author	Data Set	Location	Lapse Rate (°C/100m)
Chen et al., 2018	Ground Stations	Mt. Kenya	0.44
Mizuno & Fujita, 2014	Ground Stations	Mt. Kenya	0.63
Coe, 1967	Temperature loggers	Mt. Kenya	0.54
Grab et al., 2004	Temperature loggers	Mt. Kenya	0.68
Winiger, 1981	Soil Temperature Loggers	Mt Kenya	0.52
Loomis et al, 2017	NCEP reanalysis data	East Africa	0.58
Loomis et al, 2017	Temperature Loggers	Rwenzori	0.59
This Study	HOBO Loggers	Mt. Kenya	0.61
This Study	HOBO Loggers	Mt. Elgon	0.70
This Study	TerraClimate Reanalysis	Mt. Kenya	0.50
This Study	TerraClimate Reanalysis	Mt. Elgon	0.59
This Study	Ground Stations	Mt. Kenya	0.53

(Chen et al., 2018; Coe, 1967; Grab et al., 2004; Loomis et al., 2017; Mizuno & Fujita, 2014; Winiger, 1981)

4.3 Discussion

4.3.1 Climate trends

The warming seen in Koitobos and Teleki valleys of 1.5°C over 60 years is consistent with mountain warming trends reported around the world over the past century, which range from 0.10°C to 0.40°C/decade (Bradley et al., 2009; Donat et al., 2014; Mark & Seltzer, 2005; Schauwecker et al., 2014; Vuille et al., 2003). The trend is a monotonic increase across the whole time series. While there is definite increasing trend in temperature in the Teleki and Koitobos valleys (increasing by 0.24 to 0.28°C per decade), there is no clear trend for precipitation (Figure 4-2). This too is in keeping with other studies around the globe that have found clear trends for temperature due to climate change, but not precipitation (IPCC, 2018; Vuille et al., 2003). The relationship between global warming and precipitation is complicated, particularly in mountainous regions where there can be large variations over short spatial and temporal scales (Bacchi & Villi, 2005). Precipitation patterns are also confounded by the regular ENSO cycles which can obscure long terms trends. Reanalysis datasets do a good job capturing climate means, but they probably miss the extreme events (Hijmans et al., 2005; Mountain Research Initiative, 2015; Saha et al., 2010).

The temperature lapse rates calculated in this study are similar to historically reported values (Table 4-10). For Mount Kenya, the lapse rate from TerraClimate came to 0.50 °C/100 m from the base to the top (~2000 m -5000 m), while the Hobo data over a much shorter range (3000 m-4000 m) recorded a higher value of 0.61 °C/100 m (Figures 4-4 and 4-17). The values for Mount Elgon were higher (0.59 and 0.70 respectively), although the last value is based on an even narrower range (3400 m – 4100 m). Nonetheless these values are still within the ranges reported in the literature. The theoretical moist adiabat for East Africa is 0.55 which holds until roughly 5000 m elevation after which it increases again (Loomis et al., 2017). Global warming, theoretically, will eventually lead to a reduction of the lapse rate- a less steep slope- because higher elevation areas are predicted to warm faster than lower elevation areas (Loomis et al., 2017; Urrutia & Vuille, 2009). This does not appear to have occurred yet in Mount Kenya or Mount Elgon. The TerraClimate data displayed a remarkable consistency in slope by decade, and those values remain similar to historically reported values. It is not clear why Mount Elgon would have a steeper lapse rate; but it may just have to do with site specific factors around each temperature logger.

Precipitation generally increases with elevation to a point and then decreases again. This pattern is due to the processes of orographic uplift: as clouds rise over the mountain, they cool and reach a point where condensation occurs and they release their water (Roe, 2005). This appears to occur between 3000 m and 4000 m (Figure 4-5). With a warming climate it might be expected that this zone of maximum rainfall would move up in elevation as all the hydrological components shift up in response to warming (Huss et al., 2017); this however is not yet evident for Mount Kenya and Mount Elgon.

The ground station temperature data in Mount Kenya is interesting. Although these data only go back as far as 1992, the decline in temperatures, particularly since 2008 is unusual (Figure 4-6). There have not been other indications of a cooling during this time frame in Kenya, in fact most studies have indicated increased warming in Kenya starting from the early 1990s (Ayugi & Tan, 2019; Ongoma et al., 2018). This decline is likely a function of sensor degradation – and indeed the sensors had to be changed out twice over the time period. Sensor errors are quite common in meteorological station data, and are often due to poor maintenance or poor siting of the probes (Brown & Russell, 2010; Fiebrich et al., 2010). A study in China of some 726 stations with at least 50 years of data, found that 37% had inconsistencies in one variable or another; these inconsistencies affected long-term trend patterns (Feng et al., 2004). In fact, such inconsistencies-together with missing data and poor coverage- means that temperature satellite data actually outperforms ground station data for trend analyses (Mendelsohn et al., 2007). The Met Station data reads roughly 1 °C cooler than the in-situ logger data and satellite data for the year 2021/2022. But as each data source has its own potential sources of error, it is hard to say for sure which is the most correct reading (Appendix A1).

4.3.2 Seasonal variability and discharge trends

On the western slope of Mount Kenya, monthly variability in temperature is negligible (Figure 4-8), but it is quite substantial for precipitation, with prominent March - May (MAM) and September - November (SON) rainy seasons (Figure 4-10). As in the Teleki Valley, there is little overall trend in precipitation on the western slope (Figure 4-9), and even changes in seasonal patterns are muted (Figure 4-11). The forest service stations surrounding the mountain, however, do show changes in seasonal precipitations patterns, and several of these stations also record significant negative overall trends. The season that appears to be affected most is the short dry season- June - August (JJA) which shows significant declines in precipitation for the Hombe and Kabaru stations located to the southwest. The largest decline in total precipitation, however, comes from the Nanyuki station in the northwest (Table 4-3). Seasonal changes in precipitation patterns have been recorded before in Kenya and in this region. Precipitation from the long rains (MAM) decreased from 1979 to 2011, but increased during the short rains (SON) (Schmocker et al., 2016). Other studies have also shown that inter-annual variability of the short rains has been one of the biggest changes in the region. As SON rains generally come from the east- the Indian Ocean- they are very much influenced by changes in Indian Ocean Sea Surface Temperatures (Camberlin et al., 2014); MAM rains come from the south are less affected (Konecky et al., 2014; Messmer et al., 2021).

The slight changes in precipitation are then amplified in the streamflow data, as the stream concentrates precipitation over the whole watershed. The response is further magnified by other land-use changes that have occurred over and beyond the climate changes. Significant negative trends in streamflow were discernable over the past 50+ years (Table 4-4 and Table 4.5). The area west of Mount Kenya has had large changes in land-use cover and increases in population (Kiteme et al., 2008; Notter et al., 2007), which has put a toll on the available water on this drier side of the mountain. Particularly on the lower river gauges, the impact of increased abstractions has drastically reduced streamflow over the last 40 years (Liniger et al., 2005). But there have been significant changes in streamflow even at the A3 gauge, which is less affected by land-use changes.

The A3 gauge is located at the edge of the forest and its contributing catchment remains largely forested, nor are there any major water abstractions upstream from A3. Although the average flow at A3 has not changed (MK p=0.10), there is a significant decline in low flow (MK p<0.01) (Table 4-5), and there is a large increase in peak flows, particularly in the last decade (2005-2015) (Figures 4-15 and 4-16). The precipitation gauges above A3 - Gate Station and Met Station - do not display trends in precipitation over the course of the time series, suggesting that the changes in flow at A3 are more a function of melting glaciers and changes in hydraulic connectivity. As the alpine areas warm, glaciers melt increasing water inputs into the system, and the capacity of the system to regulate water decreases as wetlands dry up and soils lose their high organic properties and water storage capacity (Buytaert et al., 2011). The overall impact of this is an increase in volatility of the system, decreased base flows and increased peak flows (Huss et al., 2017).

4.3.3 Temperature and soil patterns

The seasonal and diurnal temperature patterns recorded in the Teleki Valley are similar to those reported in the literature. A mean monthly range of 1.7 °C and daily range of 9.8 °C found in this study (Table 4-7) are similar to the values reported by Coe (1967) of 1.7 °C and 8.9 °C, respectively. The rapid warming in the morning is also similar, with warming in excess of 10 °C in just half an hour as reported by (Hedberg, 1964; Young & Robe, 1986). However, this level of warming was only encountered once over the course of the year, whereas the historical studies reported this level of warming with only a few days' worth of data.

According to Hastenrath (1991), the elevation of the free atmosphere at which mean temperature is zero is 4750 m, while for minimum temperature it is 3500 m. Hedberg (1964) estimated similar values for the alpine regions of Kenya. However, in this study only 88 frost days occurred at the 4000 m contour over the 14 months, amounting to just 21% of the days. This is in contrast to Grab et al. (2004) who in 1999 recorded 98% of the days to be frost days at 4200 m at the surface, and 70% at 1cm depth. In Mount Elgon also, the number of frost days at 4000 m was just 46% (over a 5 month period) compared to 63% in 1997 at 3750 m (Table 4-9) (Wesche, 2002). This may indicate an overall increase in the freezing height in Kenya since the late 1990s. Satellite data has recorded an increase in the 0°C isotherm of the atmosphere over much of the tropics over the past half century; in East Africa it has averaged around 1-2 m/yr. (Bradley et al., 2009). A warming experiment in a tropical alpine region of Ecuador, found that warming led to more increases in minimum (night-time) temperatures than maximum temperatures (Duchicela et al., 2021).

The highest elevation loggers (4200 m logger on Mt. Kenya and 4100 m on Mt. Elgon) are outliers (Table 4-9) (Appendix C1), and yet reveal interesting characteristics about microclimates in these alpine areas. The highest elevation Mt. Kenya logger was placed well above the freezing line, and yet the temperature only dropped below freezing once from September, 2021 to February, 2022. The insulating effects of rocks and soil (Hedbergs & Hedberg, 1979; Young & Robe, 1986) allow for the creation of thermal refugia which are doubtless exploited by the wildlife. Indeed rock hyrax were seen in abundance in the vicinity of the 4200 m logger on Mount Kenya.

Soil properties appear not to have changed much at least since the 1980s. Soil properties generally fell within the range of historically reported values (Appendix C2), with the exception of nitrogen. It is understandable that soil properties would not be immediately sensitive to small changes in temperature, as soil processes operate on much larger scales. The relationship between soil properties and elevation is weak across the elevation span covered (3200 m- 4200 m), and the Spearman's correlations of soil properties with temperature are also fairly weak (Figure 4-20). The lack of soil pattern by elevation presents a bit of a mystery. Most studies in alpine environments find a clear linear relationship between soil organic carbon and nitrogen and elevation (Ma & Chang, 2019; Tashi et al., 2016). The reason for this is that in colder environments microbial activity reduces, slowing down the breakdown of organic material (Buytaert et al., 2011); thus one expects higher organic material at higher elevations. In a study in the Himalayas, altitude accounted for 73% of the variation in soil organic carbon and 47% of the variation in nitrogen. Soil cations were similarly positively correlated with nitrogen and carbon (Tashi et al., 2016). Nonetheless some other studies have found a less clear relationship between elevation and carbon, which is explained by additional abiotic factors such as topography and humidity as well as biotic factors such as soil fungi diversity which can play as large or larger a role as elevation (Zhu et al., 2022). The possible decrease in nitrogen found in this study would be consistent with a warming environment, but then one would expect a corresponding decline in carbon and a relationship with elevation, which was not seen in this study. It is therefore more likely that the decline in nitrogen was just a function of sampling noise and does not represent an actual change since the 1960s.

The positive relationship between maximum temperature and most of the soil properties is also counter-intuitive. This may be explained simply because Mount Elgon was the warmer mountain and also the one with the higher concentrations of carbon, nitrogen and the cations. The higher soil organic matter content on Mount Elgon could simply be a function of higher humidity on the mountain and not be related to temperature at all. The south-eastern Mount Elgon and the western face of Mount Kenya both represent the lee-sides of the mountain, although Mount Elgon does not have as distinct a rain-shadow as Mount Kenya does (ACCESS, 2015; Coe, 1967). Interestingly, however, the more pronounced diurnal temperature fluctuations on the south-eastern slope of Mount Elgon (higher maximums, lower minimums) normally would suggest clearer skies and thus drier conditions (Sklenář et al., 2016). It is not clear, therefore, what is driving this broader thermal envelope in Mount Elgon. The lower level of metals on Mount Elgon- particularly iron- is likely a function of Mount Elgon being a much older mountain (Gehrke & Linder, 2014), with more long-term weathering and leaching.

4.4 Summary

There is evidence that climate has changed in the alpine regions of Mount Kenya and Mount Elgon over the past half century. The clearest indication is in temperature trends, which exhibit monotonic increases of 1° to 2°C over the 60 year period available in the TerraClimate dataset (0.20 °C/decade). Unfortunately, the only ground station anywhere near the alpine zone is the Met Station on Mount Kenya, and its data is suspect given the sensor was replaced. The other datasets however concur that there has been a steady increase in temperatures. In-situ logger data further lend support to this trend, as minimum temperatures are several degrees higher than those reported in historical studies from the 1960s-1980s.

Other than temperature, however, there has been little significant change. Precipitation patterns do not appear to have changed much, nor has the temperature lapse rate or the diurnal temperature patterns, or soil properties. The tropical alpine temperature and soil patterns are still very much as described in the literature. These processes likely change at a much slower rate than average temperatures. There has, however, been significant changes in streamflow. While total precipitation has not changed much, there are slight seasonal changes in precipitation and these changes are magnified in the streamflow. Streamflow coming off of Mount Kenya in particular has declined over the last 30 years and in particular base flow has declined, while peak flows have become more variable. These are also the changes that are of most importance to the surrounding communities.

Chapter 5 VEGETATION PATTERNS OF THE TELEKI VALLEY OF MOUNT KENYA

5.1 Introduction

This chapter focuses exclusively on the Teleki Valley in Mount Kenya, to investigate changes in the plant communities from 1980 to the present. It draws extensively from the Young & Peacock (1992) paper whose data formed the baseline for the resurvey. Readers are directed to that paper and other papers by Dr. Truman Young from the 1979-1980 field campaign. Additional baseline data is provided by the survey efforts of Dr. Olov Hedberg in the late 1940s and H. Rehder and E. Beck in the mid-1980s. The first section studies overall changes in the plant communities of Teleki Valley, looking for evidence of mortality or vegetation shifts. The next section then examines the *Dendrosenecio keniodendron* species and changes in demography between two time periods (1980 and 2021). Finally, general patterns are explored by comparing current photographs with historical photographs and quantifying the vegetation clustering patterns across the valley.

5.2 Results

5.2.1 Plant communities of Teleki Valley

5.2.1.1 Changes in overall plant community types

The plant community types in Teleki Valley in 2021 were broadly similar to those described in the literature. Figure 5-1 displays the plant communities in the valley according to the Rehder et al. (1988) classification scheme, and as compared to the original map (see Table 2-4, pg. 25). At the lower end of the valley there are communities of F- type (*Erica/D. keniensis*), which blend into K-type (*D. keniensis/L. keniensis*) as one moves up in elevation. The upper end of the valley bottom is mostly N-type (*Carex* Bog), while the slopes are dominated by M-type (*D. keniensis/D. keniondendron*) and O-type (*L. telekii/D. keniodendron*), and the upper ridge-tops are dominated by R-type (Open *L. telekii*) or S-type (*Sencio keniophytum*). The main difference from 1988, is that in 2021 the coverage of Carex Bogs have reduced, restricted to just the higher elevation valley bottoms, while the K and F types (*D. keniensis/L. keniensis* and *Erica/D. keniensis)* have expanded as has the tussock grass/*Alchemilla* shrub community (P-type). The species changes associated with these shifts are listed in Table 5-1 as well as the valley positions where these changes have mostly occurred.

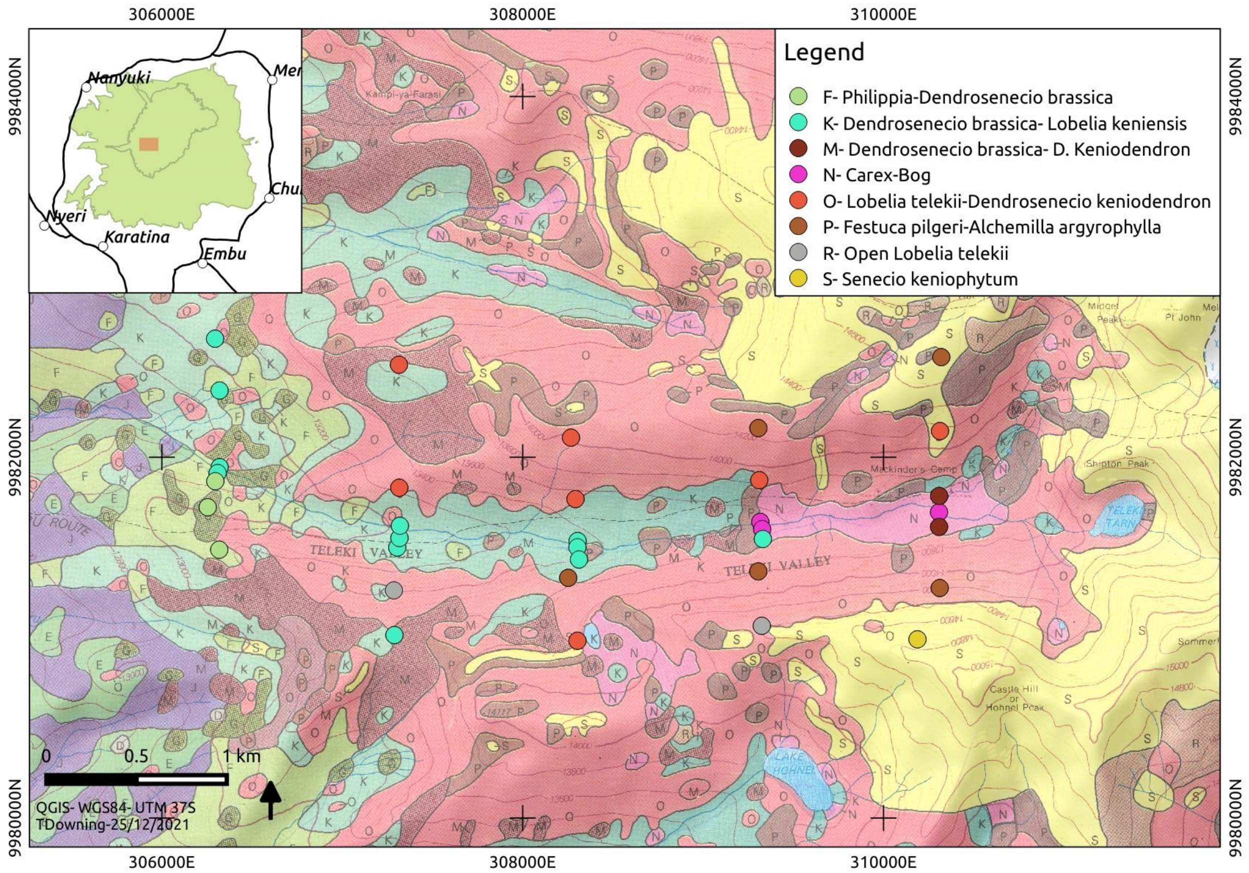

Figure 5-1 Plant community types according to transects in 2021 overlaid on the vegetation basemap of Rehder et al., 1988

Table 5-1 Major changes in plant communities from 1980 to 2020 according to Rehder type

Position	**From**	**To**	**Major change**
Valley Bottoms	N- *Carex*-Bog	M- *Dendrosenecio keniensis- Dendrosenecio keniodendron*	Expansion *Dendrosenecios* in the valley
Mid-slope	O- *Lobelia telekii- Dendrosenecio keniodendron*	P- *Festuca pilgeri- Alchemilla argyrophylla*	Increase in grass/shrubs at the expense of *D. keniodendron* midslope
Ridge	S- *Senecio keniophytum*	P- *Festuca pilgeri- Alchemilla argyrophylla*	Increase in grass/shrubs as the expense of *S. keniophytum* on the ridges

5.2.1.2 Changes in species richness and diversity

Overall, most of the sites had lower species diversity in 2021 than in 1980. The Simpsons Diversity Index for the whole valley declined from 0.82 to 0.74 (W=963, $p<0.01$) and declined for almost every site (on average of 0.06 lower) (Figure 5-2). In both periods, species diversity declined with elevation, with the valley bottom points having the highest diversity. The rate of this decrease (-0.14 to -0.16 per 1000 m) was similar between the two time periods (Figure 5-3).

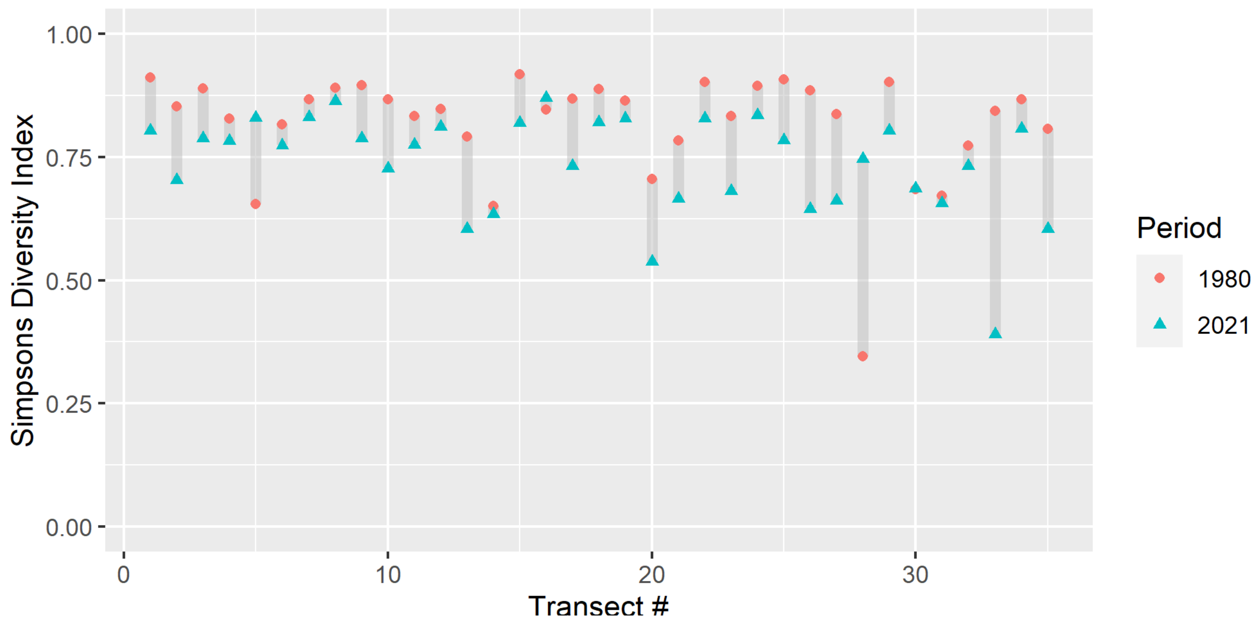

Figure 5-2 Changes in species diversity by transect number (Simpsons Diversity)

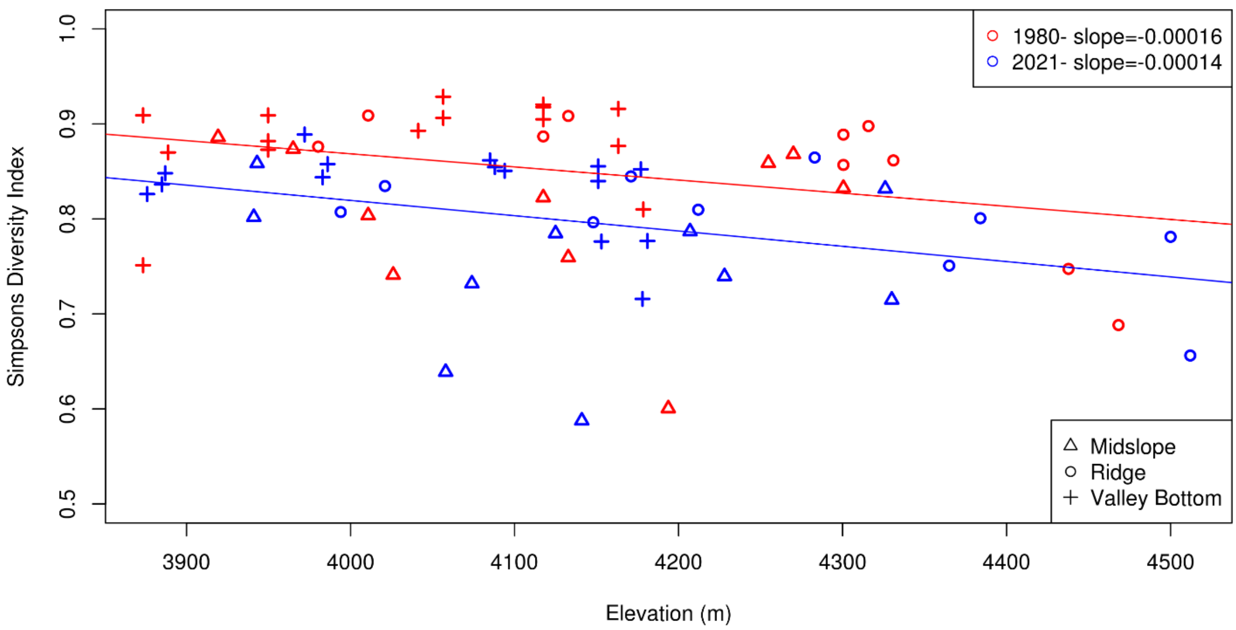

Figure 5-3 Simpson's diversity by elevation in 1989 and 2021

The total number of vascular species recorded - 33 - is comparable to previous studies in Teleki Valley (ranging from 13-61 see Table 2-3, pg. 24), but less than what was found in the 1980 study (45 excluding graminoids). While no new species were recorded, there were several species identified in the 1980 but not found in 2021. Of particular note is *Cerastium* spp. which was found in 73 quadrats (29% of the total) in 1980, but not found at all in 2021. Other species with notable declines include *Senecio keniophytum, Arabis alpina, Luzula abyssinica, Ranunculus oreophytus* and *Haplosciadium abbyssinicum* (Table 5-2). These plants are either part of the ridgetop *Senecio keniophytum* community (S-type) or the valley-bottom *Carex*-bog communities (N-type), which generally declined from 1980 to 2021 (Table 5-1). The only species to show increases were *Helichrysum cymosum*, *Erica* spp, and *Afrosciadium friesiorum.* These were generally part of the tussock grass/scrub communities (P-type) that increased in particular on the mid-slopes between 1980 and 2021 (Figure 5-1).

Table 5-2 Select species with notable change in abundance between 1980 and 2020 (species found in at least 5 quadrats (1%) in either period)

Species	***# of quadrats 1980***	***# of quadrats 2021***	***% change***
Increasing from 1980-2021			
Afrosciadium friesiorum	1.5	7	367%
Helichrysum cymosum	8.5	19	124%
Erica spp.	18.5	30	62%
Decreasing from 1980-2021			
Senecio keniophytum	37.5	0.5	-99%
Luzula abyssinica	64	4	-94%
Valeriana kilimandscharica	21	1.5	-93%
Montia fontana	5.5	0.5	-91%
Haplosciadium abbyssinicum	91.5	9.5	-90%
Galium Glaciale	31.5	6	-81%
Crepis dianthoseris	22	3.5	-81%
Sagina afroalpina	48	10	-79%
Ranunculus oreophytus	153.5	48	-69%
Swertia volkensii/crassicula	34.5	13	-62%
Arabis Alpina	16	7.5	-53%
Disappearing between 1980- 2021			
Cerastium spp.	73.5	0	-100%
Subularia monticola	17.5	0	-100%
Crassula granvikii	7	0	-100%
Alchemilla cyclophylla	5	0	-100%

5.2.1.3 Elevation shifts

Of the most constant species (present at <15% of sites in both time periods (Table 5-3), eight (8) shifted downward from 1980 to 2021 (mean shift of -24 m), while 11 shifted upward (mean shift of 43 m) (Figure 5-4).

Table 5-3 Mean elevation and constancy for species in 1980 and 2021 (listed are species with >15% constancy in both time periods).

Species	**Constancy* (% of sites occupied) 1980**	**Mean Elevation (m.a.s.l) 1980**	**Constancy (% of sites occupied) 2021**	**Mean Elevation (m.a.s.l) 2021**	**Shift in Elevation (m)**
Arabis alpina	23	4372	14	4313	-59
Helicrysum brownei	40	4045	43	4012	-33
Swertia volkensii/crassicula	40	3991	17	3958	-33
Senecio purtschelleri	23	4288	26	4265	-23
Erica arborea/Phillipia	20	3995	23	3975	-20
Ranunculus oreophytus	60	4061	46	4051	-10
Romulea keniensis	37	4114	20	4106	-8
Haplosciadium abbyssinicum	51	4115	26	4111	-4
Dendrosenecio keniensis	57	4001	46	4004	3
Alchemilla johnstonii	86	4068	83	4079	11
Sagina afroalpina	46	4122	17	4135	13
Dendrosenecio keniodendron	94	4174	37	4203	29
Lycopodium saururus	17	3986	20	4022	36
Haplocarpha rueppellii	49	4029	51	4066	37
Carduus platyphyllus	37	4235	31	4272	37
Lobelia telekii	69	4172	46	4216	44
Lobelia keniensis	66	4039	71	4084	45
Alchemilla argyrophylla	51	4124	46	4198	74
Luzula abyssinica	57	4052	11	4200	148
Helichrysum cymosum	26	4100	17	4334	234

**Constancy is percent of sites occupied out of the 35 valley positions*

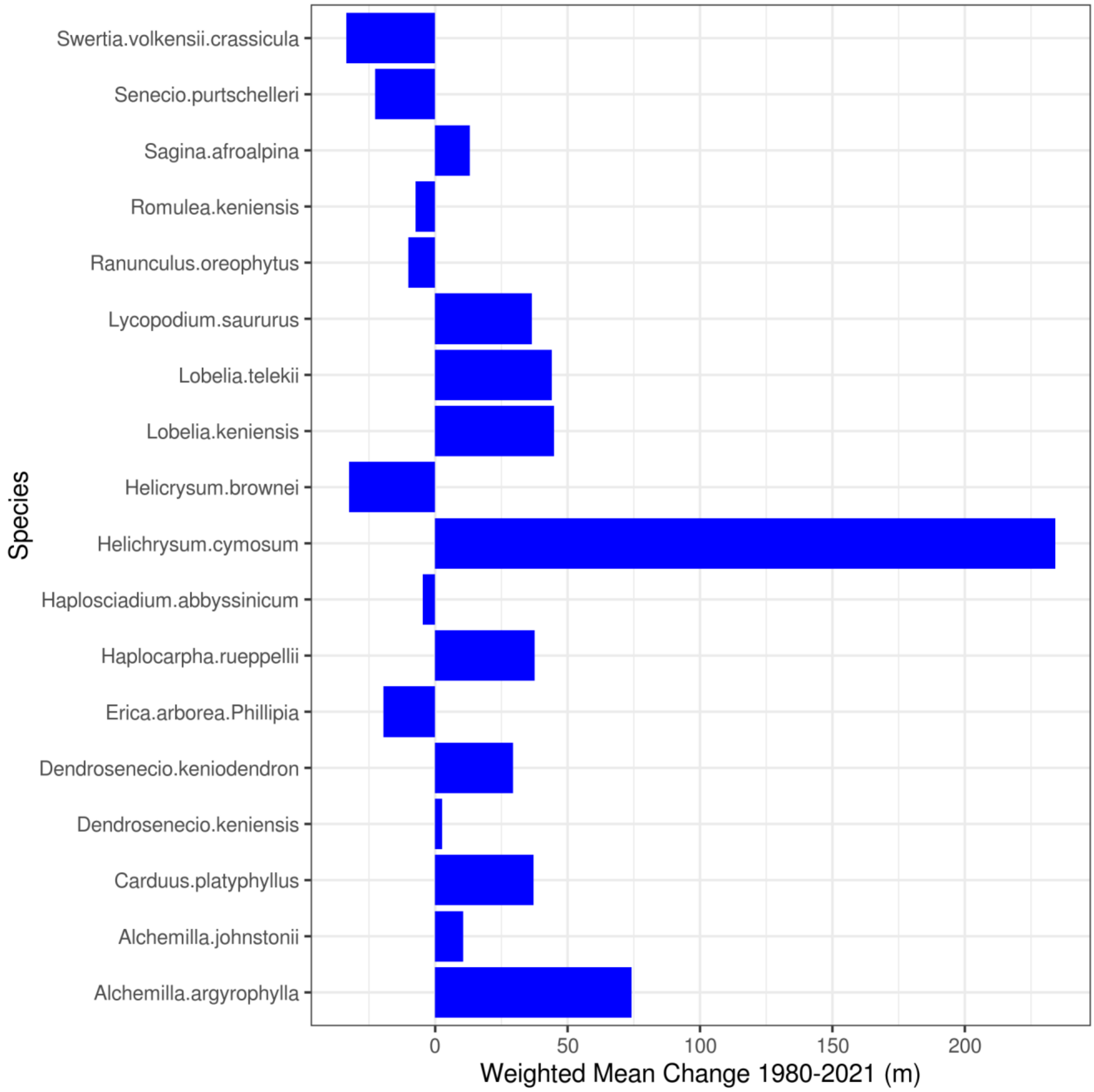

Figure 5-4 Change in weighted mean elevation for each species (>15% constancy) between 1980 and 2021

5.2.1.4 Distribution changes of the dominant taxa

The dominant species in the valley (excluding grasses) are *Dendrosenecio keniensis, Dendrosenecio keniodendron, Lobelia keniensis, Lobelia telekii, Erica arborea,* and *Alchemilla argyrophylla.* To this list can be added *Helichrysum brownei*, since it is also an important species as noted by Hedberg (1964). The last three (*Erica*, *Alchemilla*, and *Helichrysum*) were pooled at the genus level both for a larger sample.

There was very little significant change in the relative abundance of these taxa between the two time periods. *Alchemilla* spp. was the most prevalent genus (besides tussock grasses) in both time periods, found in 77% and 80% of the quadrats in 1980 and 2021 respectively (p=0.71). The other dominant species were found in much lower frequencies, <25% of the quadrats, but again showed no significant change over the 40 year period. The only species to show any significant change was *D. keniodendron*, whose frequency declined from 12% to 8% (p=0.01) (Table 5-4).

Table 5-4 Changes in the frequency (quadrats occupied out of 350) of dominant taxa between 1980 and 2021

Species	**1980**	**2021**	**p=value***
Lobelia keniensis	55 (16%)	75 (21%)	0.30
Lobelia telekii	50.5 (14%)	40 (11%)	0.16
Dendrosenecio keniensis	58 (17%)	56 (16%)	0.64
Dendrosenecio keniodendron	40.5 (12%)	29 (8%)	**0.01**
Alchemilla spp.	271 (77%)	280 (80%)	0.71
Helichrysum spp.	40.5 (12%)	55 (16%)	0.33
Erica spp.	18.5 (5%)	30 (9%)	0.70

**bold values- significance at the 90% confidence level*

There was also very little change in species distribution between the two periods, with most of the species found in similar numbers according to elevation and valley position. Again the major change was with *D. keniodendron* which was less abundant on the ridge-tops in 2021 (5 vs. 13, p=0.01), and at the lower elevations (0 vs. 9, p<0.01). *L. telekii* also decreased in the lower elevations (10 vs. 2, p=0.05) (Table 5-5). There were no significant differences either according to valley aspect- north wall vs. south wall in either time period (Appendix C2). The upper-slope *D. keniodendron/L. telekii* community therefore appears to be the most effected, but not necessarily in the same way: whereas *D. keniodendron* appears to be shifting towards the valley bottoms, *L. telekii* is shifting towards the midslope (Figure 5-5). The two species were found together in 10 transects (out of 35) in 1980 but only in 5 in 2021.

Table 5-5 Changes in frequency (out of 350 quadrats) of dominant taxa by valley position and elevation between 1980 and 2021 (Downing et al., 2023a)

Species	**Period**	**Ridge**	**Slope**	**Valley**	**3850-4050 m.a.s.l.**	**4050-4250 m.a.s.l.**	**4250-4450 m.a.s.l.**
Lobelia keniensis	1980	13	13	29	29.5	25.5	0
	2021	20	15	40	24	49	2
*Wilcox p-value		0.18	0.97	0.35	0.93	0.46	0.12
Lobelia telekii	1980	21	16.5	13	10	17	23.5
	2021	16	19	5	2	25	13
*Wilcox p-value		0.35	0.91	0.29	**0.05**	0.98	0.36
Dendrosenecio keniensis	1980	5	4	49	40.5	17.5	0
	2021	9	5	42	44	12	0
*Wilcox p-value		0.54	0.51	0.74	0.48	0.52	-
Dendrosenecio keniodendron	1980	13	12.5	15	9	14.5	17
	2021	5	9	15	1	20	8
*Wilcox p-value		**0.01**	0.23	0.47	**<0.01**	0.71	0.26
Alchemilla spp	1980	47	93	131	122	104	45
	2021	62	92	126	99	149	32
*Wilcox p-value		0.40	0.54	0.58	0.19	0.45	0.99
Helichrysum spp	1980	6.5	4	30	17.5	21	2
	2021	26.5	6.5	22	30	8	17
*Wilcox p-value		0.19	0.93	0.91	0.16	0.58	0.13
Erica spp.	1980	6	10.5	2	18	0	0.5
	2021	8	10	12	29	0	1
*Wilcox p-value		1.00	1.00	0.61	0.34	-	0.85

**bold values- significance at the 90% confidence level*

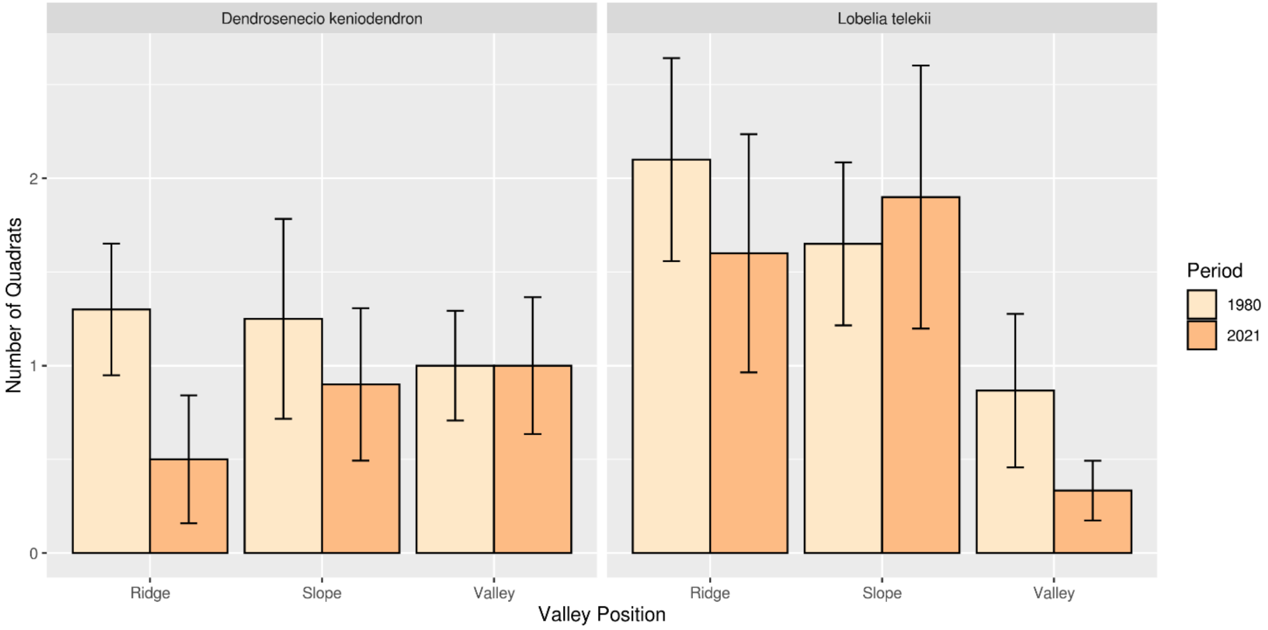

Figure 5-5 Comparison of D keniodendron/L. telekii *abundance by valley position -1980 and 2021*

5.2.2 Senecio demography in Teleki Valley

5.2.2.1 *Dendrosenecio* densities by elevation and valley position

A closer look at the two species of *Dendrosenecios* provides some more insight into how this characteristic genus has changed from 1980 to 2021. The density of *D. keniensis* has remained remarkably constant over the 40 years with similar distribution according to elevation and valley position (Figure 5-6; Table 5-6). For *D. keniodendron*, again there is an overall decline in numbers and a shift towards the valley, although not significantly so at the 95% confidence level (Table 5-6). In 1980, the authors noted the clear niche separation between the two species according to elevation and valley position: *D. keniensis* dominated at the lower elevations and then declined with elevation to very little presence by 4400 m, while *D. keniodendron* displayed the reverse pattern, peaking at around 4400 m (Young & Peacock, 1992). In 2021, the pattern for *D. keniensis* was almost exactly the same, whereas for *D. keniodendron* there was a much more flat relationship of densities with elevation. The large peak at 4400 m was no longer seen (Figure 5-6).

Table 5-6 Changes in density of Dendrosenecio *by valley position and elevation between 1980 and 2021 (Downing et al., 2023a)*

	KENIENSIS count (density #/100m²)			**KENIODENDRON (density #/100m²)**		
Position	**1980**	**2021**	**wilcox p-value**	**1980**	**2021**	**wilcox p-value**
Ridge	502 (8.37)	508 (8.47)	0.79	169 (2.82)	68 (1.13)	0.31
Slope	187 (3.12)	331 (5.52)	0.96	190 (3.17)	118 (1.97)	0.21
Valley	2007 (22.30)	1795 (19.94)	1	128 (1.42)	200 (2.22)	0.55
Elevation						
3900	1656 (27.60)	1991 (33.18)	0.52	56 (0.93)	28 (0.47)	0.36
4100	1040 (9.63)	643 (5.95)	0.99	281 (2.60)	316(2.93)	0.85
4300	0 (0)	0 (0)	n/a	150 (3.57)	42 (1.00)	0.25

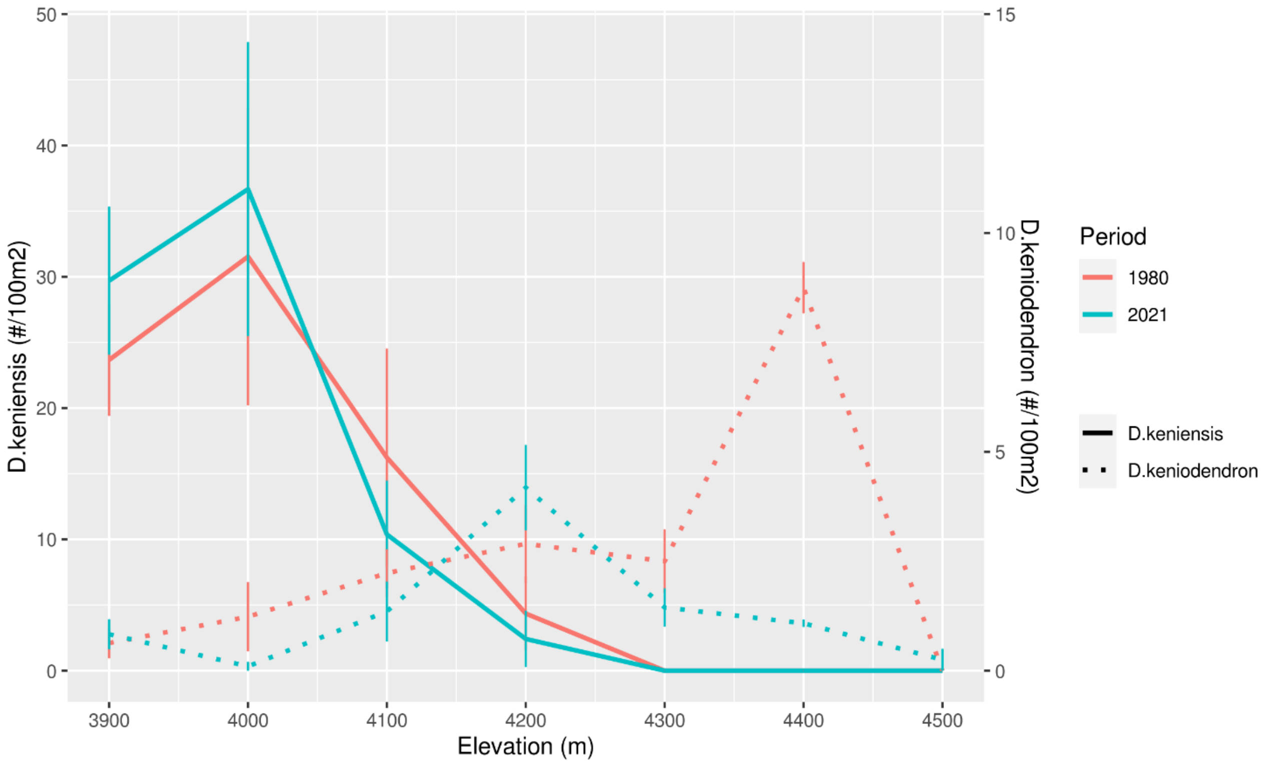

Figure 5-6 Densities of Dendrosenecios *by elevation, grouped by 100m increments in 1980 and 2021 (Downing et al., 2023a)*

<u>5.2.2.2 *Dendrosenecio keniodendron* age/size distributions</u>

Similarly, there were changes in 2021 with respect to the size class distribution of the *D. keniodendron*. In 1980, the authors found a wide range of age/size class distributions across all transects. Some exhibited even-aged structure, whereas others were heavily skewed toward to the small or large size classes, and others had a two-cohort distribution indicating a younger age group grouping up underneath an older senescent cohort (Young & Peacock, 1992). In 2021, on the other hand, there was a much more uniform pattern of uneven aged distributions across all transects. The frequency-size curves in 2021 reflect the classic inverse J-shaped curve (negative exponential) of an uneven age stand much more than in 1980 and there were very few individuals in the largest size-classes in 2021 (Figure 5-7). This pattern is most apparent in the valley bottoms; on the ridge tops, the total number of *D. keniodendron* has declined in all size classes (Figure 5-8).

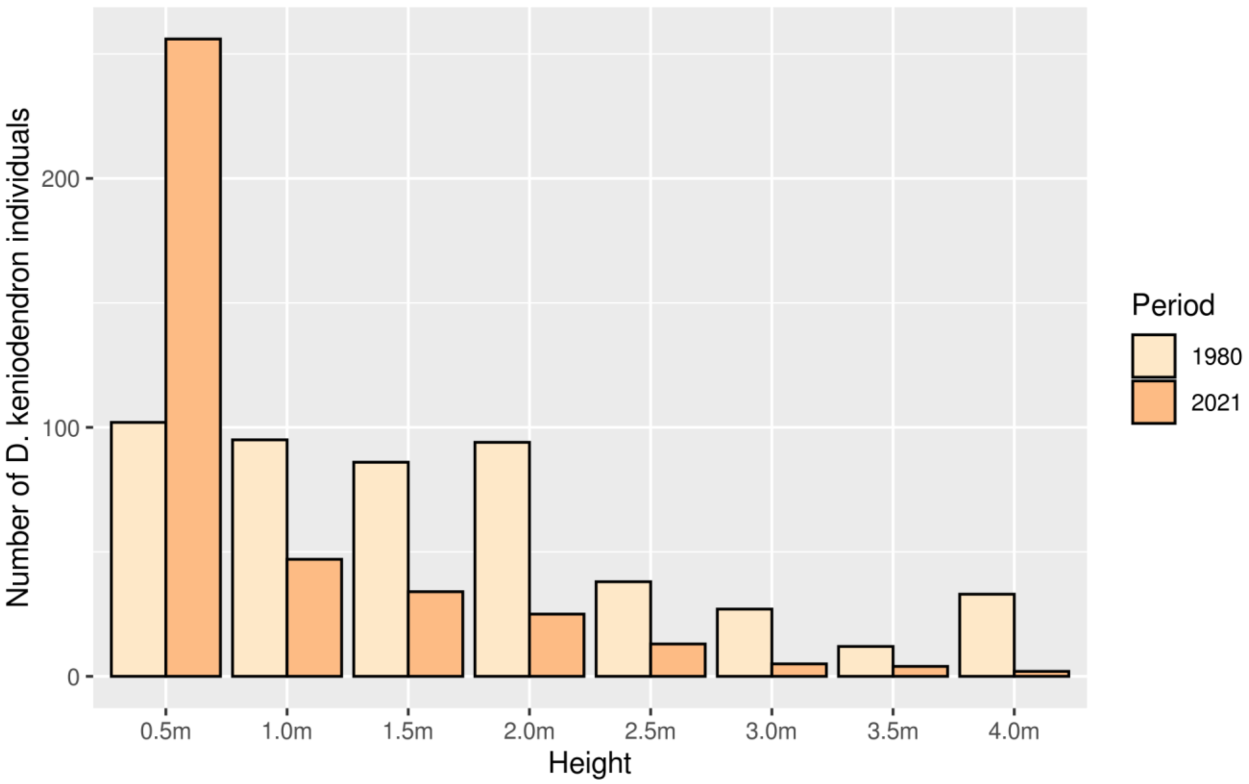

Figure 5-7 Histogram of Dendrosenecio keniodendron by height class for all valley positions – 1980 and 2021

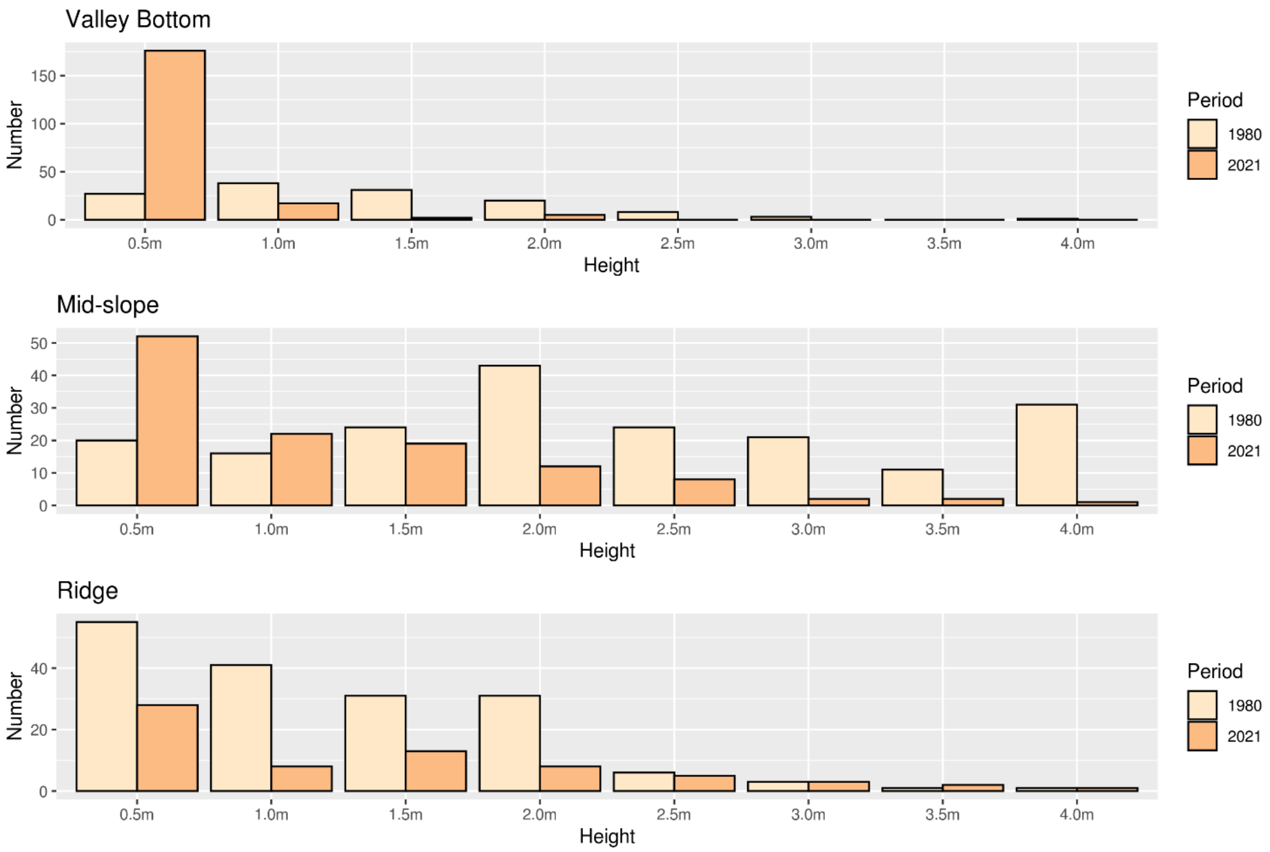

Figure 5-8 Histogram of Dendrosenecio keniodendron by height class in ridge, mid-slope, and valley bottom positions (Downing et al., 2023a)

5.2.2.3 *Dendrosenecio keniodendron* structure

Morphologically, the *D. keniodendron* show some changes from 1980. There were much fewer large individuals in 2021 and correspondingly much fewer forks on these individuals. While in 1980, 60% of the individuals had a single branch, by 2021 that had increased to 80%. The relationship between height and number of branches also changed somewhat, with a steeper relationship between number of branches and height in 1980, although this was mostly due to the higher number of branches overall in 1980. Below 3 meters, there was essentially a 1 to 1 relationship between height and number of branches (Figure 5-9). The most branches found on an individual in 1980 was 18, while in 2021 it was just 7. Interestingly, however, the total number of dead individuals was very low, across all transects only 23 standing dead individuals could be found (Table 5-7).

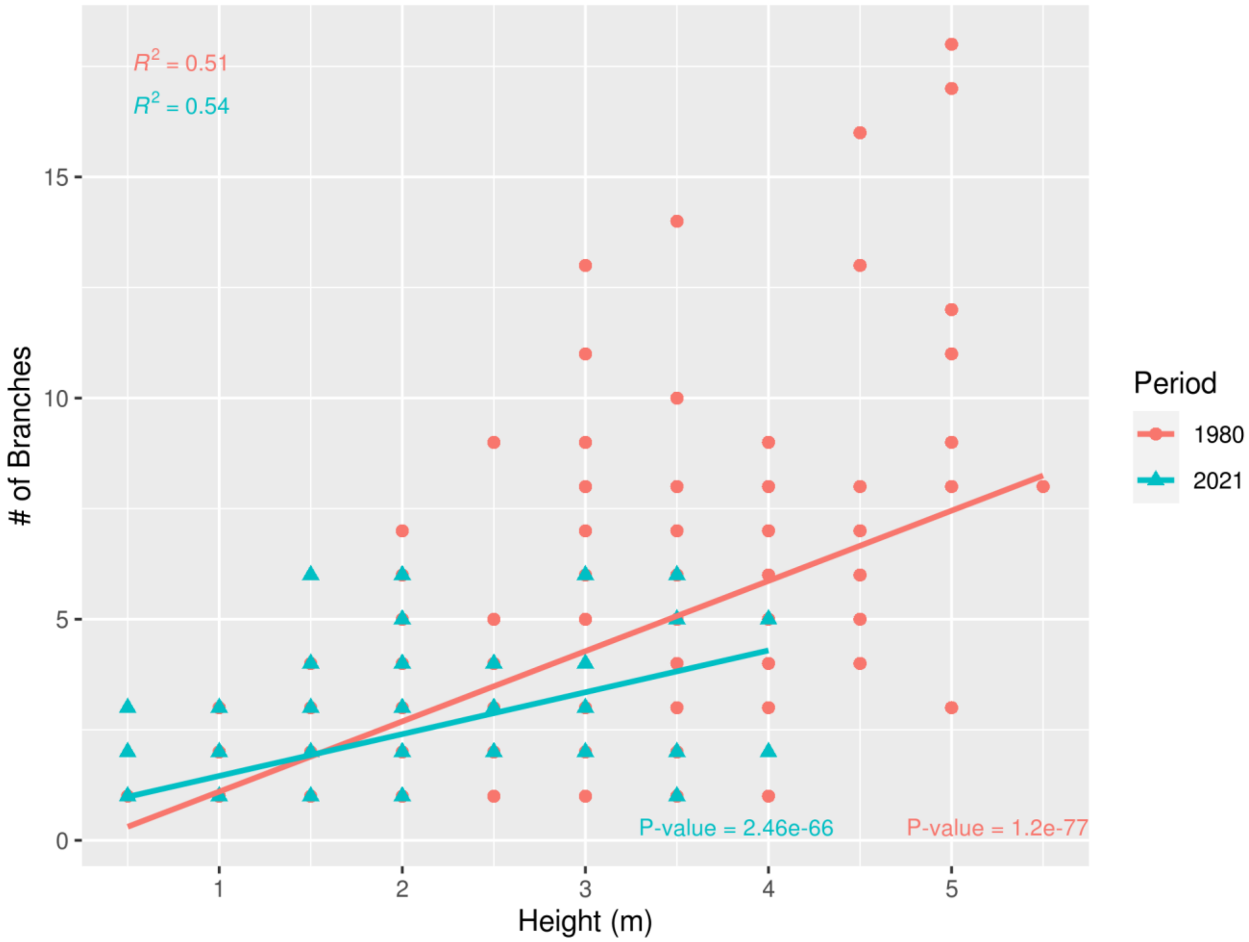

Figure 5-9 Relationship between height and number of branches for Dendrosenecio keniodendron *in 1980 vs. 2021*

Table 5-7 Counts of Dendrosenecio keniodendron *by height class (Downing et al., 2023a)*

Height class (m)	***Dead Count***	***Live Count***
0.5	6	256
1	6	47
1.5	2	34
2	5	25
2.5	0	13
3	2	5
3.5	1	4
4	1	2
Total	***23***	***386***

5.2.2.4 Environmental factors associated with plant community structure

The environmental determinants of plant community structure were similar in both periods. A comparison of biplot scores for the Canonical Correspondence Analysis (CCA) between species and environmental factors (3850 – 4450 m), shows differences primarily in the order of importance. The first axis in both years equally associated with live vegetation cover and elevation: the higher the elevation, the drier the site, and therefore the less live vegetation. The second axis then most strongly correlated with slope in 1980 but with *D. keniodendron* density in 2021. For the third axis, the pattern is reversed, correlating with *D. keniodendron* density in 1980 (with mean height a close second) and live vegetation cover in 2021 (with slope a close second) (Table 5-8). Graphing the first two axes in 2021 showed a separation between the valley bottom positions and the ridge/slope positions. Ridge and slope positions were associated with higher elevation, greater slope, and taller mean *D. keniodendron* height. Valley bottom positions were associated with more vegetation cover and *D. keniensis* density (Figure 5-10). *Dendrosenecio keniodendron* density, however, is orthogonal to these dominant trends and accounts for some of the variation not captured by elevation or valley position.

Table 5-8 Comparison of biplot scores for Canonical Correspondence Analysis (CCA) between 1980 and 2021 (Downing et al., 2023a)

	1980			**2021**		
VARIABLE	**CCA1**	**CCA2**	**CCA3**	**CCA1**	**CCA2**	**CCA3**
Live Vegetation Cover	**-0.849**	-0.260	0.369	**-0.791**	0.205	**-0.548**
Elevation	**0.832**	0.450	0.255	**0.791**	0.324	0.198
Mean *D. keniodendron* height	0.141	-0.362	**0.586**	0.751	-0.012	-0.324
D. keniodendron density	0.298	0.169	**0.609**	0.198	**0.812**	-0.053
D. keniensis density	-0.579	-0.093	-0.140	-0.676	-0.337	0.129
Slope	0.261	**-0.779**	0.486	0.476	-0.206	**-0.429**
East-West aspect	-0.003	-0.109	0.044	0.134	-0.411	0.126
North-South Aspect	-0.058	0.140	0.128	-0.302	-0.096	-0.020
Cumulative variance explained	*39.6%*	*59.2%*	*73.3%*	*44.5%*	*61.7%*	*72.4%*

**Bold values indicate the dominant factor(s) associated with each axis*

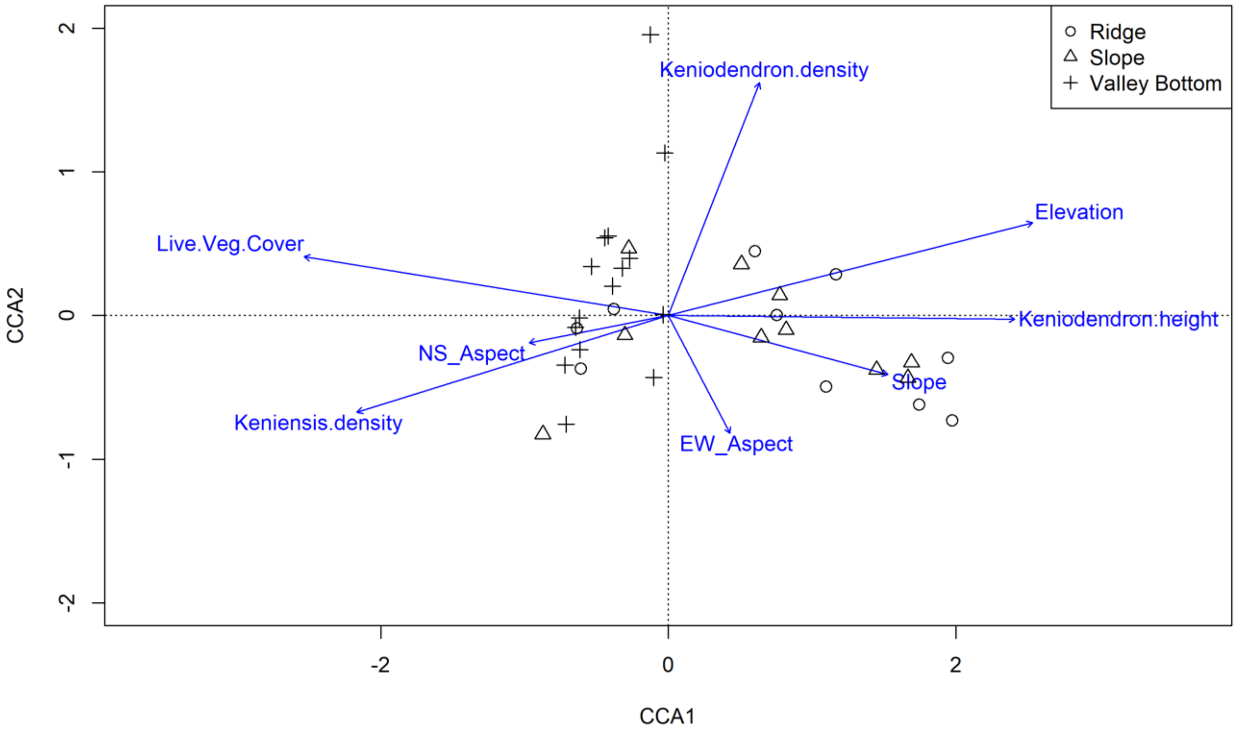

Figure 5-10 Canonical Correspondence Analysis of the 2021 transect data according to first two axes

Visualizing these changes in NMDS space illuminates these factors better. There is a significant difference between the plant communities in 1980 and 2021 (PERMANOVA F= 5.35; df =1; p<0.01) (Figure 5-11), although there is not a consistent shift according to any one underlying environmental factor. Looking just at the low altitude ridges, however, reveals two constant trends- some sites shifting towards increasing live vegetation cover (soil moisture) and others towards increasing *D. keniodendron* density/height (Figure 5-11).

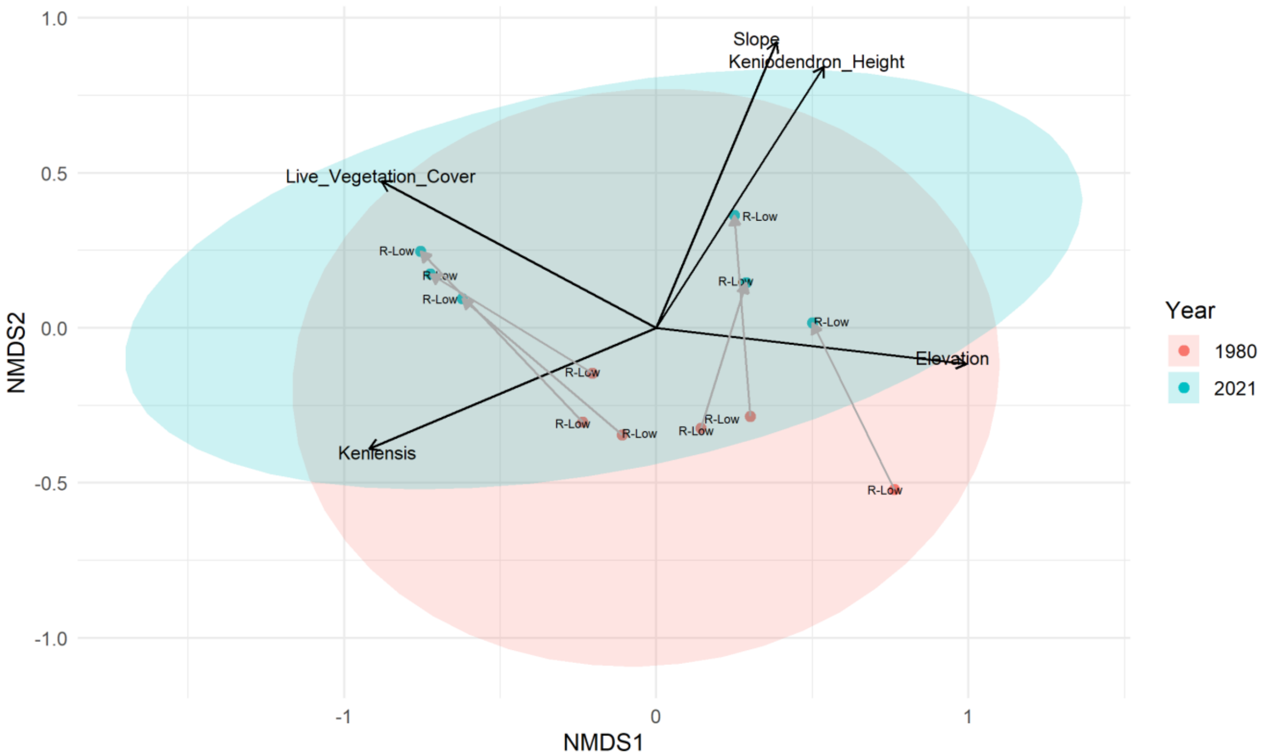

Figure 5-11 Non-metric multidimensional scaling (NMDS) plot of Bray-Curtis dissimilarity for paired sites for 1980 and 2021. Arrows show shift for each site from 1980 to 2021 (Shown are just the low elevation ridge sites -Rlow)

This strong importance of *D. keniodendron* on plant community composition was examined in 1980 with respect to the two principal shrub genera: *Alchemilla* and *Helichrysum*. The authors found that whereas older *D. keniodendron* stands were associated with higher *Alchemilla* spp. cover, they were also associated with lower *Helichrysum* spp. cover, suggesting that there is both facilitation and competition at work, and potentially alleopathy. A similar pattern was seen in 2021, although with a weaker relationship between *Alchemilla* spp. cover and mean *D. keniodendron* height (Figure 5-12; Young & Peacock, 1992).

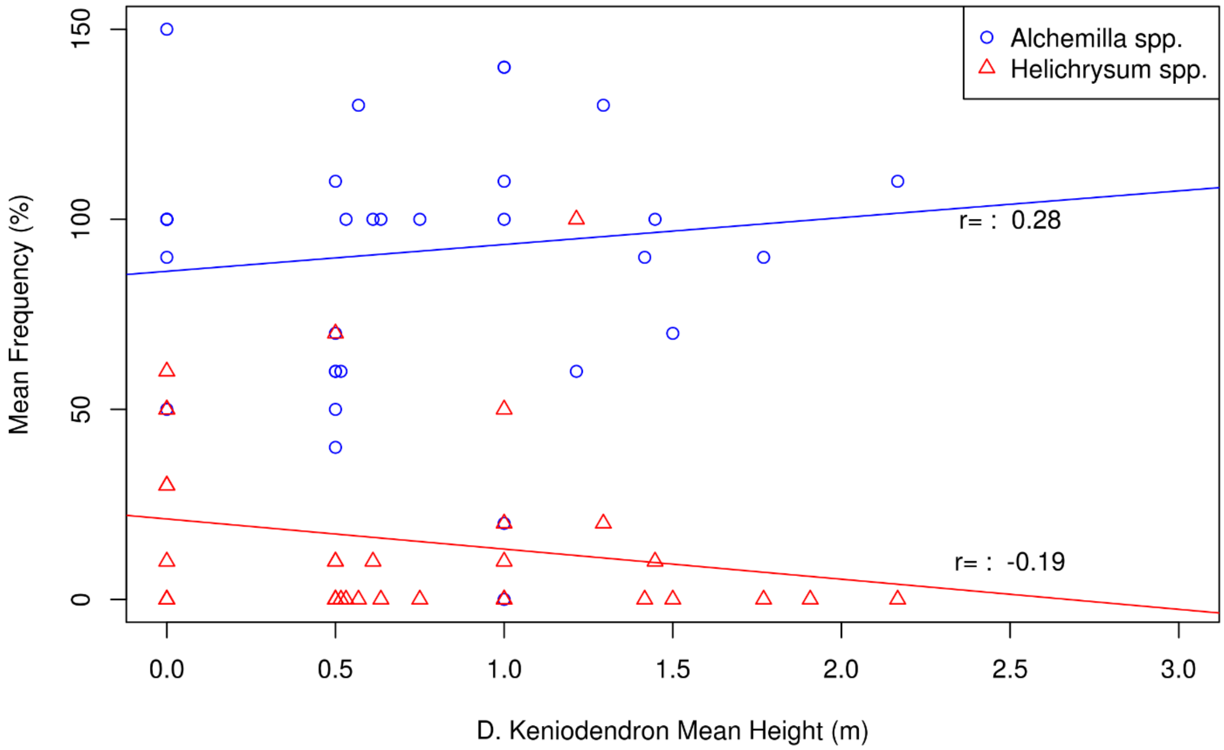

Figure 5-12 Relationship between D. keniodendron *mean height and frequency of* Alchemilla *and* Helichrysum *spp.*
** values may exceed 100% as there are multiple species in each of these genera*

Table 5-9 Correlation between mean D. keniodendron *height and frequency (quadrats occupied out of 350) of the most dominant taxa*

Species	**Correlation Coefficient- r- 1980**	**Correlation Coefficient –r- 2021**
Lobelia telekii	0.26	0.53
Lobelia keniensis	-0.09	-0.38
Dendrosenecio keniensis	-0.22	-0.59
Alchemilla spp.	0.30	-0.09
Helichrysum spp.	-0.03	-0.17
Erica spp.	-0.12	-0.31

5.2.3 Landscape patterns of Teleki Valley

5.2.3.1 Vegetative clustering

Plant-plant interactions can also be examined through landscape patterns. The size and distribution of vegetative patches reveal important details on how plants are clustering or dispersing (Berdugo et al., 2017). These patterns, quantified according to the Power Law relationship (PLR), show two distinct groupings, just as in the Berdugo et al. (2017) study. The value of PLR=0.57 separates the "PL-like" and "PL-unlike" sites. In Teleki valley, most transects had a PL-like distribution (fitting a power-curve), but the ones that fit the curve the best, were the valley bottom positions (Figure 5-13). The only ones with PL-unlike distribution (as defined as PLR<0.57) were found on the slopes and ridges. PLR also generally decreased with elevation, with the lowest values at the upper elevation ridges (Figure 5-14). This suggests a scattered distribution of vegetation on the slopes and ridges, particularly at the highest elevations, and a clumped distribution in the valley bottoms.

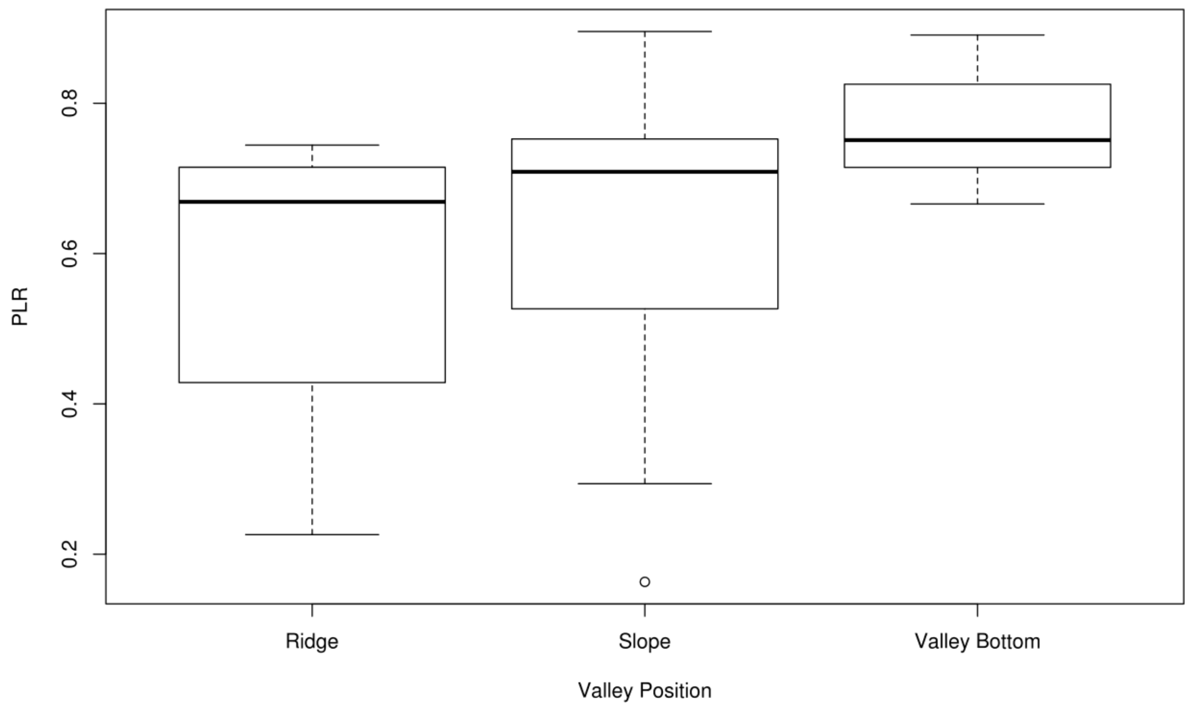

Figure 5-13 Boxplot of Power Law Relationship (PLR) for transects in Teleki Valley according valley position.

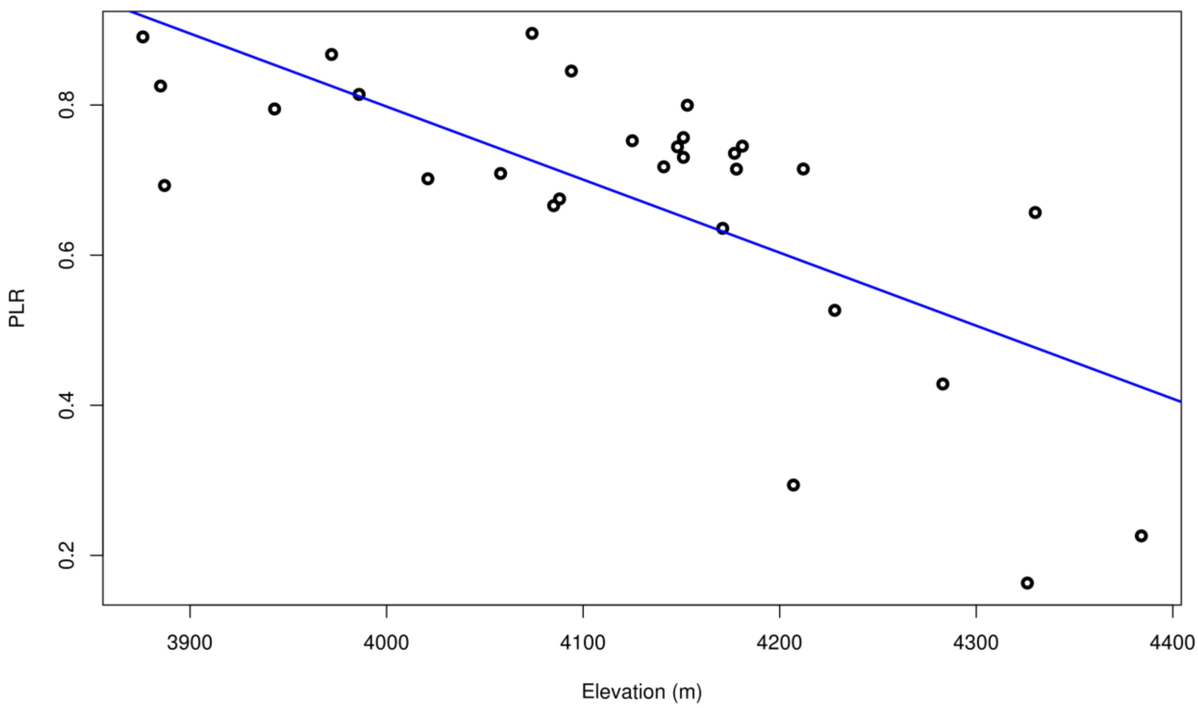

Figure 5-14 Power Law Relationship (PLR) of transects in Teleki Valley by elevation

5.2.3.2 Photographic evidence of shifts

Photographic comparisons in Teleki Valley between 1980 (or before) and 2021 reveal little definitely, and mostly suggest a consistency in the landscape. A comparison of the upper valley bowl shows a very similar landscape, dominated by tussock grasses dotted with giant Senecios. The transition between the two types of Senecios is still very apparent on the valley walls at similar positions. The photo from Hedberg (1964), which was taken in 1948, shows many flowering *L. keniensis* in the valley bottom. Thirty years later, Young (1984) commented on the lack of *L. keniensis* at the head of the valley and so speculated that the distribution of *L. keniensis* had shrunk, attributing it to a severe drought in the 1950s. In 2021 also, the upper valley bottom does appear to be more bare, with no visible *L. keniensis* influences and fewer Senecios (Appendix B2). However the quadrat data indicate actually an upward shift in elevation for *L. keniensis* as compared to 1980 (mean elevation shift of 45m- Figure 5-4) - even if not significantly so (Table 5-5). It could be that species do shift upward and downward over time in response to individual droughts and not necessarily long-term processes. Old growth pure *D. keniodendron* stands were still present in 2021 and individuals still occurred with heights well above 4 m (Appendix B2). Unfortunately the exact photograph locations of these old stands couldn't be replicated to document changes. Lower moorland grasslands of tussock grasses and *D. keniensis* dominated in both years at elevations below 3900 m (Appendix B2).

5.3 Discussion

5.3.1 Species declines

Overall species richness and diversity have declined uniformly since 1980 across all elevation and valley positions (Figure 5-3). This is somewhat counter to expectations, as elevational shifts in alpine species has generally been associated with increases in species diversity (alpha diversity) (Grabherr et al., 2010; Jurasinski & Kreyling, 2007; Salick et al., 2019; Walther et al., 2005), as more favourable temperatures allows more species to compete. The decline in diversity in this study could therefore rather be a function of the increasing aridity, which allows certain dominant species to out-compete the others. Simpsons index of diversity was lower in almost every transect in 2021 as compared to 1980 (Figure 5-2). As this index is more of a dominance index, it points to the possibility that the dominant species are expanding at the expense of some of the more rare species.

It is too soon to say whether certain species have become locally extinct. Many of these species were found in such small numbers in 1980 that a more thorough study would need to be done to fully investigate their presence. Tellingly, Rehder et al. (1988) during their almost concurrent mapping study (field work 1979-1986), did not find several of these species either, for example *Crassula granvikii, Amenome spp., Colpodium spp., Helictotrictom spp.,* or *Sedum spp.* (Rehder et al., 1988). The species in Table 5-2, however, were found in large numbers in 1980, making it unlikely that they were simply missed, suggesting they are indeed disappearing.

5.3.2 Species shifts

The elevation shifts seen in this study are consistent with shifts reported in the literature due to climate change (Lenoir & Svenning, 2015). Generally the shifts in mean elevation for species was within the range of +/- 100 vertical meters (Figure 5-4). Upslope movements in response to climate change have varied depending on the ecosystem and the taxa. Mammals, being more mobile have been shown to have shifted as much as 500 m over the last century (Moritz et al., 2008), whereas other taxa shifts have generally been on the order of 50 - 200 m (Bässler et al., 2013; Bodin et al., 2013; Dolezal et al., 2016; Konvicka et al., 2003; Walther et al., 2005). Where shifts have occurred of greater magnitude, it suggests other factors are involved beyond just climate-related factors (Bässler et al., 2013). Studies reporting shifts in modelled or optimal elevation of species have reported slightly larger shifts of +/- 200 m and sometimes larger (Coals et al., 2018; Crimmins et al., 2011; O'Sullivan et al., 2021). This may be the more accurate comparison for this study, as this study did not directly measure shifts but rather changes in mean elevation by species.

In the afro-alpine system itself, upward shifts in vegetation have been reported. In the Simien Mountains of Ethiopia, an upward shift of 120 m was documented in *Erica* spp between 1970 and 2000, (Wesche et al., 2000), and in Mount Kenya, upward shifts in *D. keniodendron* and *L. telekii* of 50 – 70 m were documented in response to the retreat of the Tyndall glacier of Mount Kenya over a 10-year period (Mizuno & Fujita, 2014). This, however, was due both to plant facilitation and soil development changes as well as air temperature changes. Going back to paleorecords, there is evidence that vegetation shifted downward substantially during the Last Glacial Maximum (LGM). In particular, *Erica* spp were some 1000 m lower during the LGM as compared to present day (Rucina et al., 2009), however not all species shifted in the same manner and the records show a mix of low altitude and high altitude species co-occurring during the LGM. Fire also was apparently a major driver of vegetation changes during the LGM, which confounds the role of temperature (Courtney Mustaphi et al., 2021).

There are few significant changes in the vegetation communities of the Teleki valley between 1980 and 2021. Most of the dominant species have remained stable in abundance, and their distribution by elevation or valley position does not appear to have changed much either. The exception is the upper-slope plant community of *D. keniodendron/L. telekii*, which appears to be declining on the ridges and recruiting in the valley. However even this pattern is slight and not consistent. The quadrat data and the size class data support this hypothesis (Table 5-5; Figure 5-8), while the overall density data is inconclusive (Table 5-6), and mean elevation for *D. keniodendron* is actually slightly higher in 2021 (Figure 5-4). *Dendrosenecio keniodendron* had lower numbers at both the higher and lower elevations (Table 5-5), causing the overall mean elevation to be higher in 2021 than 1980 (4203 m vs. 4174 m) (Figure 5-4). Probably the biggest evidence for the shift off of the ridge, however, is the changes in size class distribution, with much fewer larger individuals on the ridge and more smaller individuals in the valley bottom in 2021 as compared to 1980 (Figure 5-8). Ridgetops are drier landforms than valley bottoms (Parker, 1982; Young, 1994), and are predicted to become drier still with climate change due to increased evaporation and surface drying

(Trenberth, 2011), even if total precipitation does not change appreciably. It is therefore likely that *D. keniodendron* is responding primarily to aridity factors - facing mortality in the increasingly dry ridgetops and recruiting in the moist valley bottoms, even while at the lower elevations it may be shifting up in elevation in response to temperature.

The lack of visible mortality presents a mystery. If indeed *D. keniodendron* is being forced to shift to the valley bottoms, would not there be plenty of evidence of dead older trees? The low temperature and humidity in these environments reduces microbial activity creating for very slow rates of decay (Buytaert et al., 2011), and yet standing dead individuals in this study were very few (Table 5-7). The only explanation is that the dead individuals are consumed by fire or herbivory (Mulkey et al., 1984; Smith & Young, 1994), yet it is remarkable that these processes are so thorough in removing standing dead individuals.

5.3.3 **Dendrosenecio** ***reproduction***

The changes in *D. keniodendron* demography are interesting. In 2021 there was much less forking evident on the landscape, with the vast majority of the stands having just one (1) stem (no forks) (Figure 5-9). *D. keniodendron* fork after reproduction, so the number of forks corresponds to the number of reproduction events (Smith & Young, 1982). Single stems thus represent pre-reproductive individuals. This either suggests that the older individuals are dying off, or the reduction in number of branches reflects some physiological stress caused by climate change. In terms of age/size structure, *D. keniodendron* mostly existed in uneven aged stands characterized by an inverse J-shaped curve (negative exponential) of size distribution (Figure 5-8). In the 1980 study, on the other hand, the stands largely exhibited even-aged distributions which the authors attributed to the infrequent pulse reproduction that would allow one generation to grow and thrive as a cohort until another eventually takes over underneath senescent stands (Young & Peacock, 1992). An uneven aged distribution, on the other hand, suggests a younger stand, characterized possibly by more frequent reproductive events.

There are two main reproductive strategies employed by most plant and animal species: semelparity and iteroparity (Young, 1990). Semelparity is when organisms reproduce just once, in a large event, and then die. This strategy is often used in species living in harsh environments, where it makes sense to invest limited resources into one reproductive effort in order to increase the chance of success. Several species in Mount Kenya employ this strategy, notably *Lobelia telekii,* which generally occurs with *D. keniodendron* as a co-dominant species. By contrast, *Lobelia keniensis,* which shares habitat with *D. keniensis,* employs an iteroparous reproductive strategy- reproducing multiple times during their lifetime (Young, 1984, 1990). *Dendrosenecio keniodendron* does not employ a semelparous strategy, despite living in the harsh ridge top environments, but it does reproduce infrequently. One characteristic feature of *Dendrosenecio* communities is that reproduction happens en masse at irregular intervals known as 'mast years'. For example 1929, 1957, and 1974 were recorded as 'mast years' where at least 50% of all the specimens in the central part of Mount Kenya were found to be flowering (Beck et al., 1984; Smith & Young, 1982). One interesting observation from the Mount Kenya guides interviewed in this study is that they have perceived these 'mast years' to be happening with more frequency than they used to (see Chapter 7). This could indicate a shift towards iteroparity.

The two Mount Kenya species of *Dendrosenecio* are genetically distinct, with speciation likely having occurred due to reproductive isolation in their different habitats. Throughout the alpine regions of East Africa, Mount Kenya is the only place where habitat differences has appeared to lead to complete speciation in *Dendrosenecio* (Tusiime et al., 2020). Perhaps a consequence of a warming climate is that the two distinct species are becoming again phenotypically more similar, as they begin to occupy the same niche- forking less, but reproducing more frequently. It could also be that a hybrid species is occurring. In the 1980 study several instances of a hybrid were recorded (raw data- Young & Peacock, 1992). Ecologically, the reason for *D. keniodendron*'s unique morphology is that the height keeps the central pith away from the cold ground level and the rosette leaves further protect it from temperature swings (Hedbergs & Hedberg, 1979). This distinctive morphology of *D. keniodendron,* which was an asset on the ridgetops, may prove to be a liability in the valley as it exposes them to wind pressure.

5.3.4 Plant-plant interactions

The environmental correlates of plant community composition was similar for both years (Table 5-8). In both years, the first CCA axis separates out a similar array of species – the valley bottom species (*Lobelia keniensis*, *D. keniensis*, *Ranunculus oreophytus and Haplocarpha ruepelli*) from the ridge species (*Arabis alpina, Lobelia telekii, Carduus platyphyllus, Senecio purtschelleri*) (Figure 5-10). This axis in both years correlates most strongly both with elevation and with percent vegetation cover. While in the original CCA these two axes were distinct, with just the repeat 35 transects they are essentially the same axis. This axis thus deals with both temperature variation driven by elevation, and moisture variation reflected in the percent live vegetation cover. These are the two factors predicted to change most with climate change. The second axis (third in 1980) then correlates most strongly with *D. keniodendron* density, which points to the important role that *D. keniodendron* plays in shaping plant communities.

Researchers in Teleki valley have surmised that *D. keniodendron* functions as a keystone species that creates micro-habitats and facilitates the establishment of other species (Smith & Young, 1994; Young & Peacock, 1992). Indeed, Giant Rosette species in South America have been shown to alter soil temperatures, creating micro-climates more favourable for other plants (Mora et al., 2019). The influence of *D. keniodendron* on *Alchemilla* and *Helichrysum* abundance (Figure 5-12) provides some evidence of this keystone role, suggesting a facilitative role for *Alchemilla* but an inhibitory role for the case of *Helichrysum*.

Facilitation has long been recognized as an important component of tropical alpine ecology. In these are harsh environments, nurse plants are needed to provide micro-habitats that pave the way for other species. This enables complex plant communities to develop in harsh environments (Anthelme et al., 2014; Anthelme & Dangles, 2012; Cavieres, 2021; Hupp, 2016). Facilitation can be difficult to demonstrate in the field, so landscape patterns can be used to make inferences about these underlying processes (Alvarez et al., 2011; Berdugo et al., 2017; Hessburg et al., 1999). In their study on vegetation patterns in arid environments, Berdugo et al. (2017) found that sites characterized by plant-plant interactions exhibit a power-law distribution in patch sizes (PL-like). This is caused by clumping of plants together creating a mixture of patch sizes including large patches. As aridity increases, however, competition for water resources can prohibit development of large patches, and PL-unlike sites form, with more uniform spacing with similar sized small patches (Berdugo et al., 2019). In the current study, most transects exhibited a PL-like distribution of patch-size (distribution that follows a power-law) (Figure 5-14), suggesting that for much of the valley, facilitative plant-plant interactions dominate. However, in the upper elevation ridge-tops and slopes, abiotic factors like aridity are likely the biggest stressors, and probably prohibit plants from establishing well enough to form larger patches.

5.3.5 Inertia

Besides these shifts in *D. keniodendron,* the overall pattern in Teleki Valley is one of remarkable stability between the two periods. This stability is interesting, but not necessarily unusual. Given the slow life histories of the organisms in this environment, a rapid change would not be expected. The organisms that have adapted to these harsh environments likely have a high resilience in the short to medium term (Wahren et al., 2013). In fact, even in Arctic areas of the world that are very much in the spotlight for climate changes, there has been a remarkable stability in vegetation communities (Callaghan et al., 2022; Cirtwill et al., 2022).

The other reason for stability can be due to opposite stressors from climate change that can even offset each other, resulting in cryptic patterns of species responses to climate change. In this study, possible upward shift in elevation were documented as well as downward shifts. The two stresses associated with climate change in these environments are increasing temperature and increasing aridity, and these can result in opposing predictions for vegetation range shifts. Whereas certain species may move upwards in response to more favourable temperatures, others may move downwards in response to more favourable moisture conditions. Adaptations to aridity and cold temperature are the two most important features of plants in these harsh environments (Smith & Young, 1987), so plants would understandably be particularly sensitive to changes in these abiotic properties. These two opposing responses to climate change- upward shifts and downward shifts- have been reported before in mountain regions (Bodin et al., 2013; Coals et al., 2018; Crimmins et al., 2011; O'Sullivan et al., 2021), and in fact these studies have demonstrated that elevational niches are likely determined as much by moisture as by temperature.

5.4 Summary

There is evidence of some change in plant communities over the past half century, although by-and-large, the pattern seems to be one of inertia towards change. Both upward and downward shifts are identified, likely responding to two different stresses associated with climate change- temperature and aridity. The two forces can work synergistically or antagonistically. For *D. keniodendron*- the species of focus in this study- there is evidence of a shift towards the valley bottom, even as there is no clear trend in elevation. Overall, species diversity has declined in the valley since 1980, although it is not clear whether this is due to local extinction or just reduction in abundance of some of the rarer species. While warming would suggest more favourable temperatures and an increase in abundance and richness, this study suggests the opposite is occurring. Factors driving plant communities in these environments are complex, involving abiotic and biotic factors. *Dendrosenecio keniodendron* appears to be one of the most affected species- undergoing interesting changes in demography and potentially morphology. As *D. keniodendron* is likely a keystone species in this ecosystem, these changes may have cascading effects on the overall biodiversity of the valley.

Chapter 6 LOCAL COMMUNITIES' PERCEPTIONS OF THE ALPINE ZONES OF MOUNTS KENYA AND ELGON

6.1 Introduction

This chapter examines the human dimension of climate change around the alpine areas of Kenya. In particular it examines the views of communities located downstream from the Koitobos and Teleki valleys. Both quantitative and qualitative methods are used for this section: quantitative methods in the form of questionnaires administered to a random sample of households in the study area, and qualitative methods in the form of focus group discussions and interviews with purposefully selected individuals. For the quantitative data, categories of the researcher are used to understand climate change and adaptive capacity in the two mountains. Then the qualitative analysis allows the voice of the respondents themselves to come out. The first section deals with the use and services of the two mountains, and the factors that may explain the variability in responses. The next section then deals with changes in those ecosystems services over the lifetimes of each respondent. Differences between Mount Elgon and Mount Kenya communities are explored in detail. Finally, perceptions regarding vulnerability and adaptive capacity are examined for the whole study population, as well as any additional themes that came out in the discussions and interviews.

6.2 Results

6.2.1 Ecosystem services used by Mount Kenya and Mount Elgon communities

6.2.1.1 Demographics

A total of 209 questionnaires were administered across both study areas: 114 in Mount Kenya and 95 in Mount Elgon. Because of the distribution of questionnaires across clusters, the total came to slightly larger than the sample size calculated (Appendix A3). Respondents were largely middle aged, male, and farmers/agriculturalists with a primary school level of education. The dominant ethnicities were Kikuyu and Kalenjin (for Mount Kenya and Mount Elgon, respectively), and the majority of the respondents did not move to the area but were born there (Table 6-1). These factors largely reflect the underlying demographics of the area, and are characteristic of rural communities in Kenya. However, the low turnout of women and the elderly does reflect a sampling bias, which is mainly a function of issues of access into the community. The youth (<30 years) were also not very well represented. This may have to do with the location of the interviews, which were at households or community centres, thus missing youth who would be at school or at work sites. In terms of occupation, many fell into several categories, but only one option was allowed on the questionnaire.

Table 6-1 Questionnaire demographics (N=209) (Downing et al., 2023b)

CATEGORY	PERCENTAGE	CATEGORY	PERCENTAGE
Age		**Occupation**	
<30	31%	Farmer / Agriculturalist	57%
30-60	56%	Business owner	17%
>60	13%	Day / Unskilled laborer	9%
		Professional	5%
Gender		Government employee	1%
Female	22%	Other	11%
Male	78%		
		Ethnicity	
Education		Kalenjin	39%
Primary School	51%	Kikuyu	45%
Secondary School	39%	Meru	8%
Diploma	10%	Luhya	6%
University Degree	1%	Other	1%
Move Here			
No	60%		
Yes	40%		

6.2.1.2 Demographics by study area

Mount Elgon and Mount Kenya had similar demographics, although Mount Elgon overall displayed a more rural character. Fully three-quarters of the respondents in Mount Elgon were farmers, born in the area, and two-thirds had only a primary school level of education. In Mount Kenya, there were more immigrants than residents, and only 39% were farmers, the rest being a mix of other professions. Also more had gone to secondary school and 17% had education beyond that (Table 6-2, see also Appendix C3). This reflects the difference socio-economic situation of the two areas. Mount Kenya is located in central Kenya with a closer proximity to industry and tourism opportunities, and a greater flux of population- with people entering and leaving in search of employment.

Table 6-2 Questionnaire demographics by study area (N=209)

	Percentage	
Move Here	**Elgon (N=95)**	**Kenya (N=114)**
No	79%	44%
Yes	21%	56%
Occupation	**Elgon**	**Kenya**
Farmer / Agriculturalist	78%	39%
Business owner	5%	27%
Day / Unskilled laborer	6%	11%
Professional	4%	5%
Government employee	0%	2%
Other	6%	16%
Education	**Elgon**	**Kenya**
Primary School	65%	39%
Secondary School	32%	44%
Diploma	3%	15%
University Degree	0%	2%

6.2.1.3 Overall interaction with the mountain

When asked about the level of interaction with the mountain, most respondents rated as 'high' or 'very high' their level of engagement with the mountain, in terms of frequency of visit, importance in their life, and knowledge of the mountain (Figure 6-1). It became clear after the first few questionnaires that the interaction between the community members and the actual alpine zone was virtually none, so the questionnaire was broadened to include the mountain as a whole. Therefore the benefits that the communities indicated were not necessarily alpine services (Appendix C3).

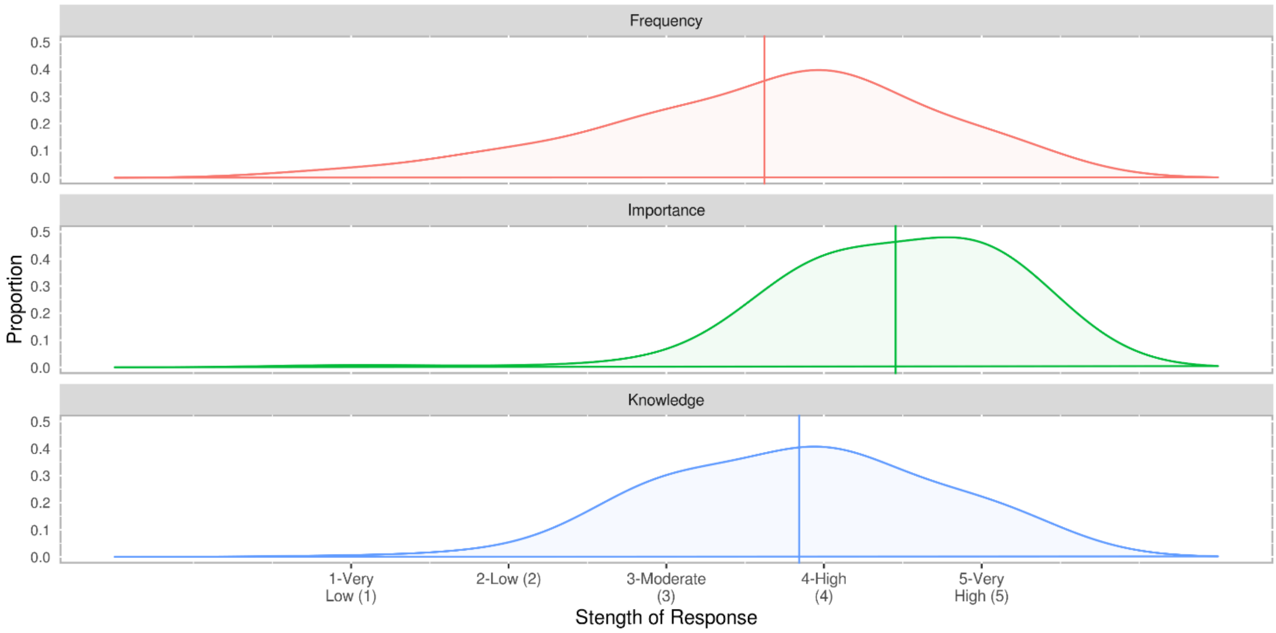

Figure 6-1 Respondents' level of interaction with mountain resources (Downing et al., 2023b)

**density curve for strength of response to questions related to interaction with the mountain. The vertical bar gives the mean response for the whole study population*

6.2.1.4 Appreciation of ecosystem services

Respondents mentioned water and forage as the most important services that the mountain provided, and to a lesser extent medicines, food gathering, and agriculture. Almost all (89%) of the respondents mentioned water as a principal benefit of the mountain. Generally they did not volunteer cultural services unless prompted (Table 6-3).

Table 6-3 Mountain ecosystem services identified by respondents

ECOSYSTEM SERVICES	**Percent of Respondents**
Forage	74%
Gathering	27%
Agriculture	51%
Medicine	25%
Water	**89%**
Recreation	10%
Ceremonies	3%

Almost all the ecosystem services were valued highly - ranked as important or very important. Although in the first section of the questionnaire people mostly just indicated water and forage as benefits of the mountain, when asked specifically about other services they generally agreed that these too were important or very important benefits from the mountain (Figure 6-2).

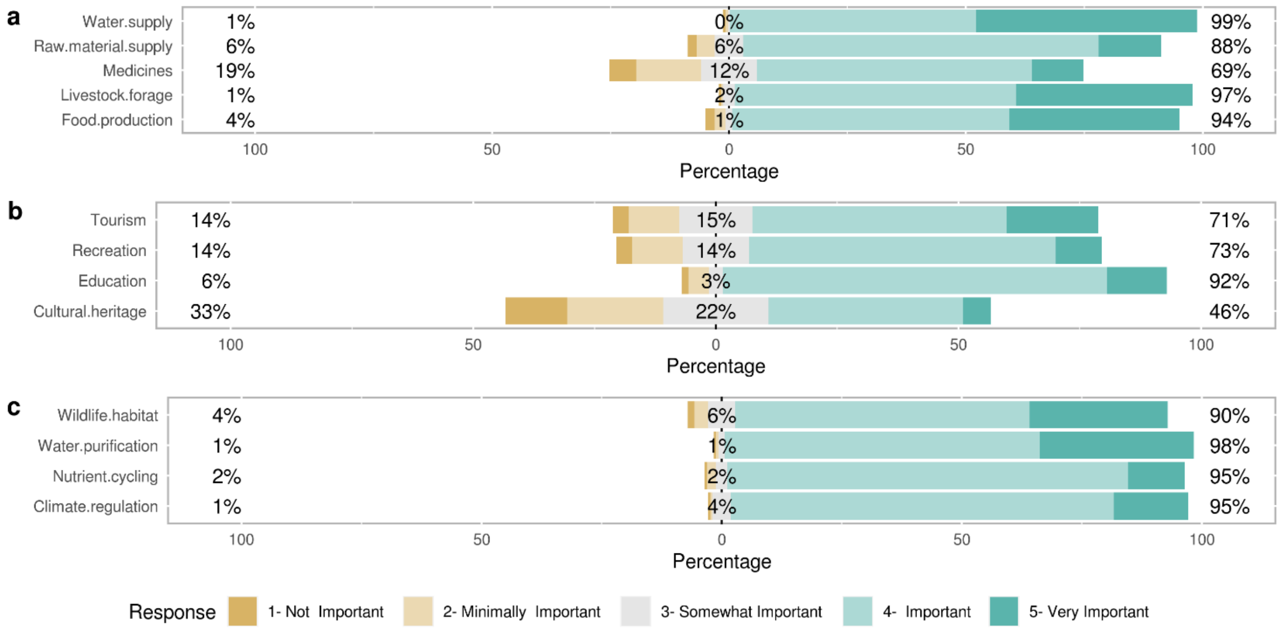

Figure 6-2 Level of importance of provisioning (a), cultural (b), and regulating (c) ecosystem services according to respondents

**bars are centred on the neutral response; area to the left indicate negative responses (not important, or minimally important), whereas area to the right indicate positive responses (important or very important)*

The highest ranked services were regulating services. These include climate regulation, provision of wildlife habitat, water purification and nutrient cycling. Each one was rated important or very important by at least 90% of the respondents. Provisioning services were ranked almost as high, with over 88% of the respondents listing these services (food, raw materials, water, and forage) as important or very important. Cultural services (tourism, recreation, cultural heritage, and medicine) were ranked somewhat lower (46% to 73% ranking them highly). Although medicines is generally thought of as a provisioning service (MEA, 2005), for many respondents it functioned more as a cultural service, as the use of medicines was closely tied to traditional knowledge. Many people pointed out that cultural and medicinal uses were something that the older generation had derived from the mountain, but was no longer a service of importance. On the other hand, educational services of the mountain ranked much higher (92%). This may, however, have been just an affirmation of the importance of education in general, as few people elaborated on the role of the mountain in education.

6.2.1.5 Factors influencing perceptions

An ordinal logistic regression showed that perceptions on ecosystem services were influenced by demographic and spatial factors. Table 6-4 gives the log-odds for each factor by ecosystem service. This is the likelihood that the reference category would rank each ecosystem service higher as compared to the other categories. Estimates were left in the log-odds form so that the sign (+/-) could indicate the direction of the interaction (the odds ratio can then be calculated as the exponent function of the estimate). So for example, immigrants (Move Here=Yes) were less likely to rank cultural heritage (-0.68) and medicines (-0.83) high as compared to long-time residents in the area. Meanwhile those with at least secondary education were more likely to rank climate regulation high (0.87) as compared to those with primary education, and non-farmers (Occupation=Other) were more likely to rank education (1.05) and water purification (0.83) high as compared to farmers.

With regard to spatial variables, those living near roads were more likely to rank culture (1.58), medicines (1.78), and tourism (1.87) high, and those living near the alpine zone were more likely to rank climate regulation (0.95) and water purification (1.01) high. The largest effect, however was with study site, with those in Mount Kenya less likely to rank culture (-1.79) and medicines (-3.97) high as compared to those from Mount Elgon (Table 6-4). Generally, the pattern was that those who interacted with the mountain more (which tended to be those from Mount Elgon who were Kalenjins farmers with a primary school level of education and born in the area) had a higher appreciation of ecosystem services (particularly cultural services) than those with less interaction with the mountain.

Table 6-4 Ordinal Logistic Regression- factors influencing perceptions of ecosystem service importance

Factor/ ES	Sex [Male]	Move Here [Yes]	Education [Secondary+]	Occupation [Other]	Ethnicity [Kikuyu]	Ethnicity [Meru/Luhya]	Distance to road [near]	Distance to alpine [near]	Study Area [Mt Kenya]
Climate regulation	-0.16	-0.53	0.87**	0.13	0.1	0.54	0.48	0.95**	-0.59
Cultural heritage	0.51	-0.68**	-0.17	0.1	-0.13	-0.12	1.58**	0.01	-1.79**
Education	0.12	-0.27	-0.43	1.05**	0.09	0.29	-0.19	-0.49	-1.11
Food production	0.01	0.11	0.14	0.57	-0.24	-0.42	-0.05	0.07	-1.69
Livestock	0.35	0.28	0.35	-0.24	-0.04	0.35	-0.14	0.1	-1.31
Medicines	0.22	-0.83**	0.04	-0.15	0.04	0.25	1.78**	0.46	-3.97***
Nutrient cycling	0.05	-0.07	-0.3	0.78*	-0.43	0.4	-0.09	0.15	-0.56
Raw materials	0.16	0.21	-0.62	0.3	-0.86	-0.32	1.43	-0.61	-1.7
Recreation	-0.18	-0.28	-0.22	0.16	0.67	0.58	0.56	0.32	-0.78
Tourism	0.35	-0.27	0.26	0.13	0.43	0.73	1.87***	0.09	-0.71
Water purification	0.53	-0.38	0.27	0.83**	-0.61	-0.48	0.38	1.01***	-0.39
Water supply #	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Wildlife habitat	0.4	0.3	0.11	-0.27	-0.91	-0.94	-0.1	0.43	0.23

** = p < .1, ** = p < .05, *** = p < .01*
+Logistic Regression Model: [Ecosystem Service] ~ Gender + Immigrant Status + Education + Occupation + Ethnicity + Distance to Road + Distance to Alpine Zone + Study Area
 # Water supply had too few levels in the responses to fit the model

6.2.1.6 Specific ecosystem services

The qualitative research component enabled the elicitation of specific ecosystem services that were of importance to the respondents themselves, rather than the general categories used in the questionnaires. Respondents made note of all three types of ecosystem services- provisioning, cultural, and regulating (Table 6-5), and had some interesting examples of each one. Provisioning services mentioned included food gathering (honey, vegetables, fruits, and fish); livestock rearing (fodder and salts); medicine (various herbs and trees); and raw materials (firewood, timber, straw and stones). Cultural services included rites and rituals (healing ceremonies, circumcisions, and fortune telling), education (coming of age ceremonies), spiritual value (prayers and fasting), and recreation/aesthetics (athletic training and a sense of home). Finally, regulating services included regulation of air, water, and soil- all of which were seen to be clean and healthy because of the mountain. The role of the mountain for supporting wildlife was also recognized which could be seen as either provisioning (use of wildlife for food), cultural (fostering tourism), or regulating (supporting biodiversity).

Table 6-5 Ecosystem services identified by interview and focus group participants (Downing et al., 2023b)

	CATEGORY	EXAMPLES	
Provisioning	Food Gathering	•hives for honey (two varieties of bees) •bamboo (young ones eaten as a vegetable) •spiky plant (can be cooked and eaten as a vegetable)	•fishing in mountain streams •collection of fruits and beans
	Livestock	•grazing in the forest and moorland; •salt and freshwater for livestock from the mountain caves	•livestock fodder from the moorlands to carry down to the settlements
	Medicine	•salt from caves has medicinal value for livestock •thistle plant used for stomach illness •other medicinal trees and flowers	•bamboo for curing stomach pains and nodes to cure malaria •milk from a certain tree used to kill intestinal worms
	Raw Materials	•deadwood for firewood or for construction •toothpicks fashioned from a certain tree •baskets or sacks made from local straw	•face paints comes from a certain tree •gathering of stones and other building materials
Cultural	Cultural practices	•coming of age/isolation rites in the forest •circumcision and healing rituals in the forest •fortune telling and prophecy	•ancestral caves for various rites- circumcision, delivery of twins
	Education	•forest as a repository of culture, a place to learn customs, traditions, and history	
	Spiritual Value	•mountain is planned/designed by God •receive blessings for daily activities from the mountain: holy shrine •praying and fasting on the mountain •conduct sacrifices on the mountain because God lives there	•the mountain is God's store with provisions for the community •it is a holy place, clean place- representing purity and sacredness •myths and legends associated with the mountain •there are specific places on the mountain with spiritual value- caves
	Recreation and aesthetics	•Special places with flowers on the mountain, nice to visit and enjoy •runners use the mountain to train and exercise	•the mountain is home, you feel good there, •tourists (usually foreigners) go in with bicycles to recreate
Regulating	Air	•clean, healthy air- keeps away disease •the forest cleans the air and takes up carbon	•trees control the movement of lightening
	Water	•the mountain (forest) brings the rains, regulates the seasons, and cleans the water •rivers comes from the mountain; there it rains all year round	•it rains on the mountain before the rest of the country; dictates climate patterns in the region
	Wildlife/	•animals are plentiful; monkeys, antelopes, elephants; squirrels, moles, lizards, snakes;	•animals are important for tourists, which supports local economy
	Soil	•trees hold in place the soil to prevent erosion and landslides	

One person summed up the role of the mountain by referring to it as "God's store":

"You can see the importance of the mountain to the local people - indigenous people- and their belief was that...God does not reside on mountains, he is all over, but mountains are his store. If it is not his dwelling house - not his state-house - then it is his store. Because this is where you get supplies - water for life." (KII #3, Mt. Kenya)

Overall, water was seen as the dominant service provided by the mountain. In all the communities, there was a clear appreciation of the role of the mountain in providing water, and people associated the mountain with water more than anything else:

"The forest has many benefits for us. Here in the mountain, the rains come according to the times that God planned, the forest itself regulates the seasons of the rain." (FGD #1, Mt. Elgon)

However cultural services of the mountain were also stressed, even if these views were not as wide-spread among the respondents. Just as the mountain was seen to be a store for physical resources, it also was seen as store for cultural resources:

"You know the forest in any part of the world, it conserves the culture of the people of that place. And it protects their language- the pronunciation and how it stays with the people- it is protected by the forest. Because the naturality of the forest- our brother here has said that it breathes- the trees breathe that natural air that's here by almighty God... So the forest retains…even if you go up to Chepkitale, there are people that live inside, and they speak the completely original language of the past. So also if the children go maybe to stay over there, they have the spirit to say they are a people of this area." (FGD #1, Mt. Elgon)

However there was equally a sense that many of these services were being lost:

"Traditions that we used to do in the forest were from a long time ago - those years ago, we would prepare children for circumcision- having been circumcised they would live in the forest for some time until they heal and then return. But these days life has changed, there is not this - it has left with the times, it is not there anymore. Also, there was the tradition of the old men, who would walk and live in the forest, because of the current life of today, this also is past - it's not there anymore." *(Mt. Elgon KII #2)*

6.2.2 Perceptions of changes on the mountains

6.2.2.1 Perceptions of changes in ecosystem services

With regard to changes, water again dominated as the number one change observed, with almost 69% of the respondents listing changes in rainfall pattern as one of the major changes they had witnessed. Temperature and soil fertility changes also featured prominently (Table 6-6).

Table 6-6 Climate changes experiences by respondents over the course of their lifetimes

CLIMATE CHANGES	**Percent of Respondents**
Temperature	42%
Species Range	19%
Species Composition	15%
Streamflow	18%
Water quality	9%
Soil fertility	34%
Rain pattern	***69%***

Perceptions of changes of individual ecosystem services were more varied, with the full spectrum of responses on display. The responses skewed towards high or very high change, but there was also plenty of responses to the contrary (Figure 6-3). People reported high change (in most cases declines) in provisioning services, particularly food (79% high or very high) and raw materials (73%), but also in cultural heritage (70%), climate regulation (59%), and tourism (57%). Medicine and cultural regulation received the highest amount of 'very high change' responses. Conversely, water purification and forage were seen to have changed the least with only 34% and 41% of respondents, respectively, indicating high or very high changes in these services.

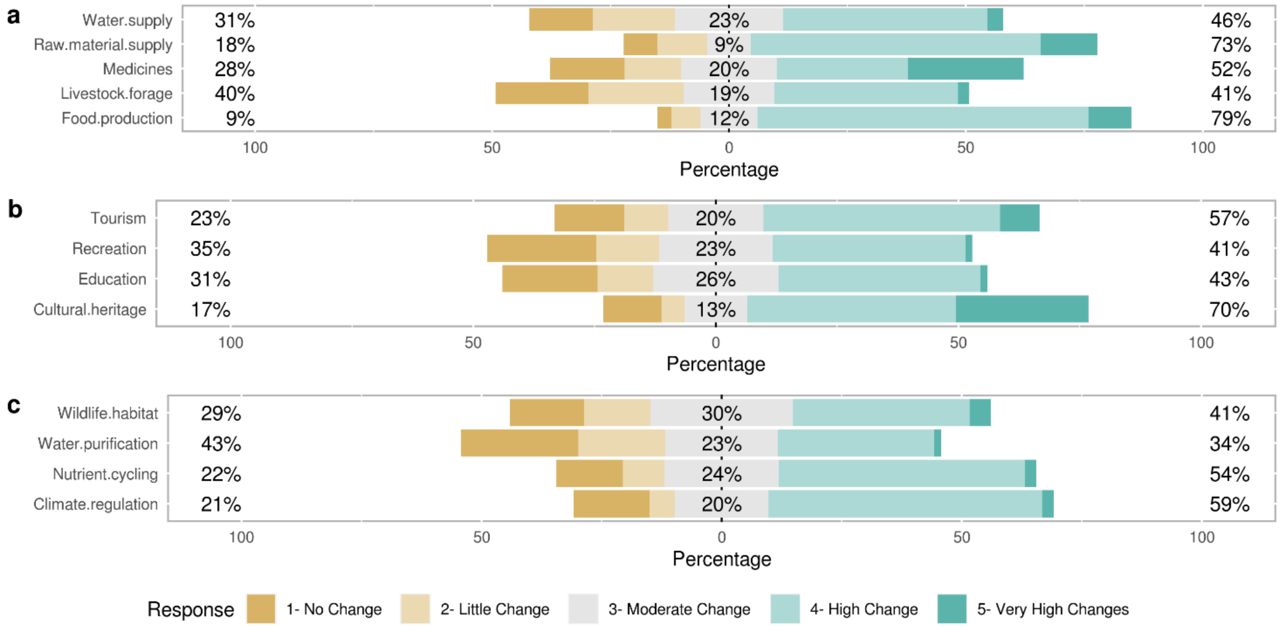

Figure 6-3 Perceived level of change in provisioning (a), cultural (b), and regulating (c) ecosystem services according to respondents

**bars are centred on the neutral response; area to the left indicate negative responses (no change or little change), whereas area to the right indicate positive responses (high change or very high change)*

When expounding on these responses, many gave conflicting views on the subject. Some indicated strongly that wildlife or water levels had decreased, while others equally strongly said they had not. In terms of nutrient cycling, water purification, and climate regulation, many people based their answers on current conditions- noting that the soil was fertile, the air was pure, and the water was clean- without directly answering the question about the role of the mountain in maintaining these qualities. For soil, many noted that they had to add fertilizer now, whereas in the past they did not. This observation thus reflects a change, but not necessarily a climate or mountain specific change, rather it could reflect population increases, overuse of soil, and deforestation. The vast majority of the changes noted were negative changes, though in Mount Kenya there were a few instances of respondents indicating changes for the better, noting increases in rainfall and air quality.

6.2.2.2 Factors influencing perceptions

The logistic regression also showed that demographic and spatial factors influenced views on changes. Males were less likely to rank changes in climate regulation (-0.75), recreation (-0.94), and tourism (-0.75) high as compared to females. Immigrants (Move Here=Yes) were more likely to rank changes in medicines high (0.65); and non-farmers (Occupation=Other) were less likely to rank changes in cultural heritage (-0.91), education (-0.74), medicines (-0.91), and recreation (-0.74) as compared to farmers.

With regard to spatial variables, those living near the alpine zone were less likely to rank changes in climate regulation (-0.83), culture heritage (-0.57), recreation (-0.98), and tourism (-1.02) high as compared to those living further from the mountain. And again study area had the largest impact, with those in Mount Kenya more likely to rank changes in medicines highly as compared to those in Mount Elgon (2.41) (Table 6-7). However, the overall pattern was not as clear: while farmers noticed more changes in ecosystems services than other occupations, those living closer to the alpine zone noticed less changes. It could be that those living closer to the alpine zone habituate easier to the changes and therefore don't notice as much the incremental changes as they occur.

Table 6-7 Ordinal Logistic Regression- factors influencing perceptions change in individual ecosystem services

Factor/ ES	**Sex [Male]**	**Move Here [Yes]**	**Education [Secondary+]**	**Occupation [Other]**	**Ethnicity [Kikuyu]**	**Ethnicity [Meru/Luhya]**	**Distance Road [near]**	**Distance Alpine [near]**	**Study Area [Mt Kenya]**
Climate regulation	-0.75**	0.16	-0.04	-0.32	-0.13	0.1	-0.75	-0.83***	1.05
Cultural heritage	-0.25	0.16	0.22	-0.91***	-0.3	-0.04	-0.44	-0.57**	1.74*
Education	-0.06	0.05	0.19	-0.74**	-0.03	0.48	0.99	-0.55*	-0.6
Food production	-0.28	-0.3	0.27	0.32	-0.37	0.21	-0.68	-0.59*	0.22
Livestock	-0.51	0.1	0.22	0	-0.22	0.01	-0.12	-0.07	0.37
Medicines	-0.5	0.65**	0.08	-0.91***	0.02	0.14	-0.64	-0.27	2.41**
Nutrient cycling	-0.41	0.09	0.15	0.07	0.05	0.85	0.28	-0.50*	-0.92
Raw materials	0.12	0.1	0.28	-0.32	0.53	0.61	-1.47*	-0.45	1.28
Recreation	-0.94***	0.19	-0.01	-0.74**	-0.02	0.47	0.74	-0.98***	-0.8
Tourism	-0.75**	0.3	-0.07	-0.35	-0.29	0.45	-0.89	-1.02***	0
Water purification	0	0.13	0.53*	-0.59	0.19	0.66	0.75	-0.36	-1.05
Water supply	-0.51	-0.49*	0.24	-0.25	-0.33	0.36	0.63	-0.06	0.33
Wildlife habitat	0.11	0.16	0.2	-0.01	-0.37	0.12	0.17	-0.39	-0.53

** = $p < .1$, ** = $p < .05$, *** = $p < .01$*
+Logistic Regression Model: [Ecosystem Service] ~ Gender + Immigrant Status + Education + Occupation + Ethnicity + Distance to Road + Distance to Alpine Zone + Study Area

6.2.2.3 Specific examples of changes

The interview and focus group respondents also brought out some interesting examples of changes for each of these ecosystem services (Table 6-8; see Appendix C3 for more specifics). Changes were noted in wildlife and vegetation (elevation shifts, growth rates, and species), climate (ice disappearance, seasonal changes, rainfall pattern), and declines in the quality of soil and air. There were some very specific indicators of changing temperature, particularly from the guides who often had particular benchmarks to compare current conditions. The most remarked upon changes again had to do with changes in the water cycle, both in rain patterns and in streamflow:

> *"When I was born, yea? When the forest was still very thick - there was a lot of rain. The wind could blow from a lower region like Lake Victoria, when it reaches the mountain, it is drawn by the strength of the forest, and it rains - there was a lot of rain....but because of this destruction, there is little rainfall." (KII #2, Mt. Elgon)*

Not only had rainfall pattern, but even the characteristics of rainstorms themselves:

> *"It has come to change even the lightning...it hits people at night, it hits cows at night, it hits things haphazardly. We've seen that if this forest doesn't return in our country - it's like the trees used to control the movement of this lightning - the air." (FGD #1, Mt. Elgon)*

6.2.3 Comparison of views from Mount Elgon and Mount Kenya

6.2.3.1 Overall perceptions by study area

Overall, respondents from Mount Elgon ranked the importance of ecosystem services higher than those from Mount Kenya, with the exception of tourism which was ranked lower in Mount Elgon. The largest differences were for cultural heritage (mean score of 2.87 in Mount Kenya vs. 3.32 in Mount Elgon) and medicines (3.08 and 4.15, respectively) (Table 6-9). The only significant differences between the two mountains in perceptions of change, were for culture, medicines, and tourism. Culture and medicines were perceived to have changed more in Mount Kenya (mean scores of 3.90 and 3.85) than Mount Elgon (3.44 and 2.72, respectively), whereas tourism was perceived to have changed less (3.11 for Mount Kenya; 3.47 for Mount Elgon) (Table 6-9). These perceptions were likely a function of different level of engagement with the mountain, with those in Mount Elgon being more frequent visitors and ranking the mountain as more important in their everyday life (Figure 6-4).

Table 6-8 Environmental changes identified by interview and focus group participants

Category	Examples	Category	Examples
Vegetation	•moss growing higher up •plants blooming/flowering more often •lichen only in higher elevation •pines and other plants shifting higher up •giant rosettes starting to die in lower elevations •new plants species appearing •plants becoming smaller in the higher elevations •plants growing faster and bigger •loss of certain tree species: Elgon Teak, cedar and olive	*Temperature*	•glaciers reduced (routes becoming unstable) •Lewis glacier moved 30m in just 10 years •Snow line/freezing line shifting up- to 4200m •less snow on the mountain (or no snow) •ice caves disappearing •ice routes becoming extinct- don't use ice axes anymore •warmer days- you feel you are getting burned •also colder nights- some of the coldest nights ever experienced recently •Mosquitoes now present at elevations where before there were none.
Wildlife	•animals rarer at higher elevations •animal ranges expanding- birds going lower; lions going higher •loss of honey bee species •loss of various wildlife species- fish, snakes, elephants	*Rain Pattern*	•daily pattern changing, no rains in the morning •hail has increased •rains coming from any and all directions now •lightning has increased •unpredictability of rains- just don't know when it will rain •storms forming suddenly •more rain intensity causing landslides
Soil	•loss of solifluction [soil ice crystals] in the moorlands •soil in the moorland more stable than before •erosion and loss of topsoil in the forest •landslides •loss of soil fertility and organics	*Rain Seasons*	•seasons changing- expect April to be wet but now it's dry; raining in September and January when it's supposed to be dry •uncertainty in seasons- rains either come early or late; can rain any month now. •planting season is shorter than before
Air Quality	•foreign trees bringing foreign air •decline in air quality	*Water Quantity/ Quality*	•total rain has decreased •moorland is becoming drier •tarn lake levels sinking; glaciers and culling ponds reducing •permanent rivers becoming seasonal or drying up completely •snow no longer builds up on the mountain

Table 6-9 Differences between perceptions for communities around Mount Kenya and Mount Elgon

	IMPORTANCE			CHANGE		
SERVICE	Mean Score Kenya	Mean Score Elgon	Mann-Whitney*	Mean Score Kenya	Mean Score Elgon	Mann-Whitney
Climate regulation	4.11	4.15	0.49	3.30	3.19	0.09
Cultural heritage	2.87	3.32	**0.01**	3.90	3.44	**0.00**
Education	3.91	4.09	**0.02**	2.98	2.89	0.28
Food production	4.07	4.51	**<0.01**	3.68	3.85	0.15
Livestock	4.21	4.53	**<0.01**	2.92	2.75	0.43
Medicines	3.08	4.15	**<0.01**	3.85	2.72	**0.00**
Nutrient cycling	4.01	4.15	**0.04**	3.11	3.30	0.24
Raw materials	3.89	4.05	**0.02**	3.68	3.51	0.08
Recreation	3.68	3.67	0.75	2.87	2.82	0.80
Tourism	4.04	3.43	**<0.01**	3.11	3.47	**0.01**
Water purification	4.26	4.39	0.05	2.65	2.73	0.64
Water supply	4.36	4.60	**<0.01**	3.18	2.92	0.09
Wildlife habitat	4.06	4.28	**0.01**	2.88	3.16	0.09

**P-value for Mann-Whitney (U) test*

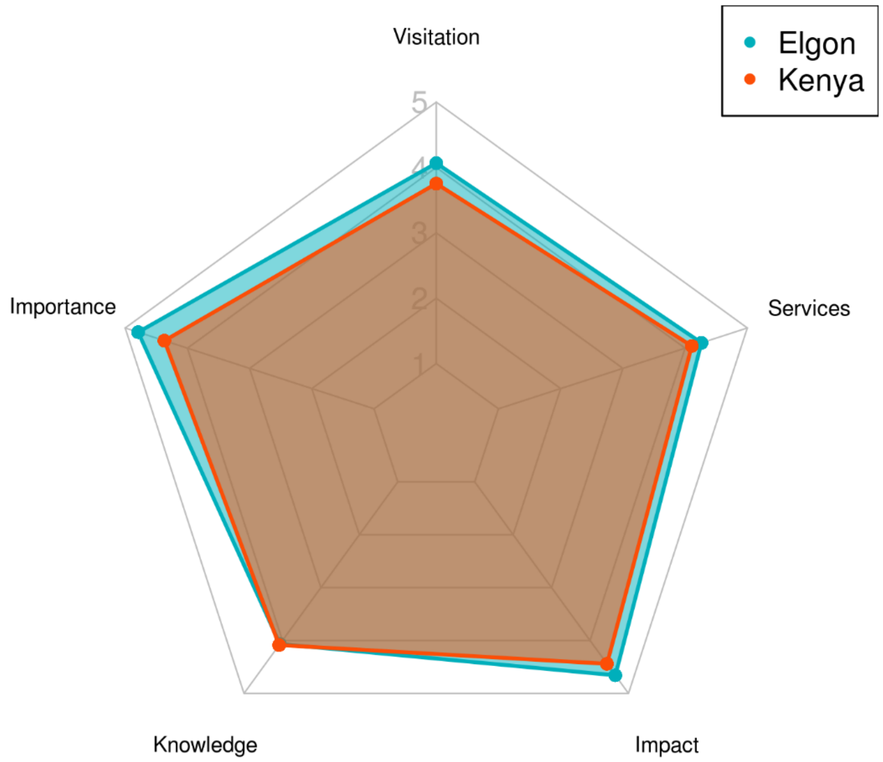

Figure 6-4 Radar chart showing mean level of agreement to statements related to interaction with the mountain

** mean strength of agreement scores for statements regarding importance, knowledge, impact and frequency of visit for the two mountains (see Appendix A3), combined with a mean ecosystem service appreciation score*

Study site was an important factor influencing perceptions, as seen in the large and significant log-odds values both for appreciation of ecosystem services and changes in those services. It also appears to best separate the data in multidimensional space. A multiple-correspondence analysis was run on the entire dataset of likert-scale responses, and study site showed the clearest separation. Mount Elgon and Mount Kenya are clearly separated according to the 95% confidence ellipses (Figure 6-5).

Figure 6-5 Multiple Correspondence Analysis in questionnaire data with confidence ellipses according to study area

6.2.3.2 Level of engagement by study area

As with the questionnaire data, there were some noticeable differences in qualitative data between the Mount Elgon communities and the Mount Kenya communities (Table 6-10). Overall, the Mount Elgon interview and focus group participants seemed to appreciate the ecosystem services of the mountain more than the Mount Kenya participants. All the services, with the exception of the water regulating, received more mention in the Mount Elgon discussions. On the other hand, there were more mentions of climate changes in Mount Kenya: with temperature changes being raised on 15 separate occasions in Mount Kenya versus 6 in Mount Elgon. Many of these were detailed examples of changes, whereas in Mount Elgon the changes mentioned were often much more broad.

Table 6-10 Comparison of how frequently different themes were raised in Mount Kenya versus Mount Elgon

COMPARISON	**Count of mentions in Interviews and Discussions**	
Category	**Mount Elgon**	**Mount Kenya**
Ecosystem Services	Food Gathering (9) Livestock (8) Medicine (9) Raw Materials (6) Cultural (11) Education (3) Spiritual (10) Recreation/Home (7) Wildlife/Tourism (8) Air (3) Water (6) Soil (1)	Food Gathering (3) Livestock (2) Medicine (1) Raw Materials (1) Cultural (0) Education (0) Spiritual (8) Recreation/Home (1) Wildlife/Tourism (3) Air (1) Water (10) Soil (0)
Climate Change	Vegetation (3) Wildlife (5) Soil (4) Air (2) Temperature (6) Rainfall Pattern (6) Rainfall Season (3) Water Quantity/Quality (4) No Changes (7)	Vegetation (11) Wildlife (4) Soil (6) Air (0) Temperature (15) Rainfall Pattern (3) Rainfall Season (7) Water Quantity/Quality (8) No Changes (5)

** interviews and discussion transcripts were coded according to the themes of ecosystem services, climate changes, and adaptive capacity. 286 statements were so coded*

6.2.4 Vulnerability, resilience, and adaptive capacity

6.2.4.1 Views on the threat of climate change (both mountains)

The majority of respondents agreed or strongly agreed that the mountain provides important ecosystem services that are free and available to all with additional value beyond what they themselves get from the mountain. Over 90% of respondents agreed or strongly agreed to these statements. Similarly, most people saw the mountain to be vulnerable to climate change and that services had declined over the years (89%), though fewer people seemed worried that it might be lost forever if changes continue (73%). In terms of adaptive capacity, a majority felt that they would be able to deal with future climate change impacts (65%) and that they had the support they needed (63%) (Figure 6-6). Nonetheless, these responses were less strongly held: while respondents were willing to strongly agree to the importance of the mountains (and strongly disagree that it the resources were lost it would have no impact on their lives), few people were willing to strongly agree to their ability to handle changes in the future. Follow-up comments suggested that their agreement was less due to optimism and more due to an inherent stoicism. Many expressed little confidence in local institutions to manage climate change. Some simply said that would have to rely on God as they have always done.

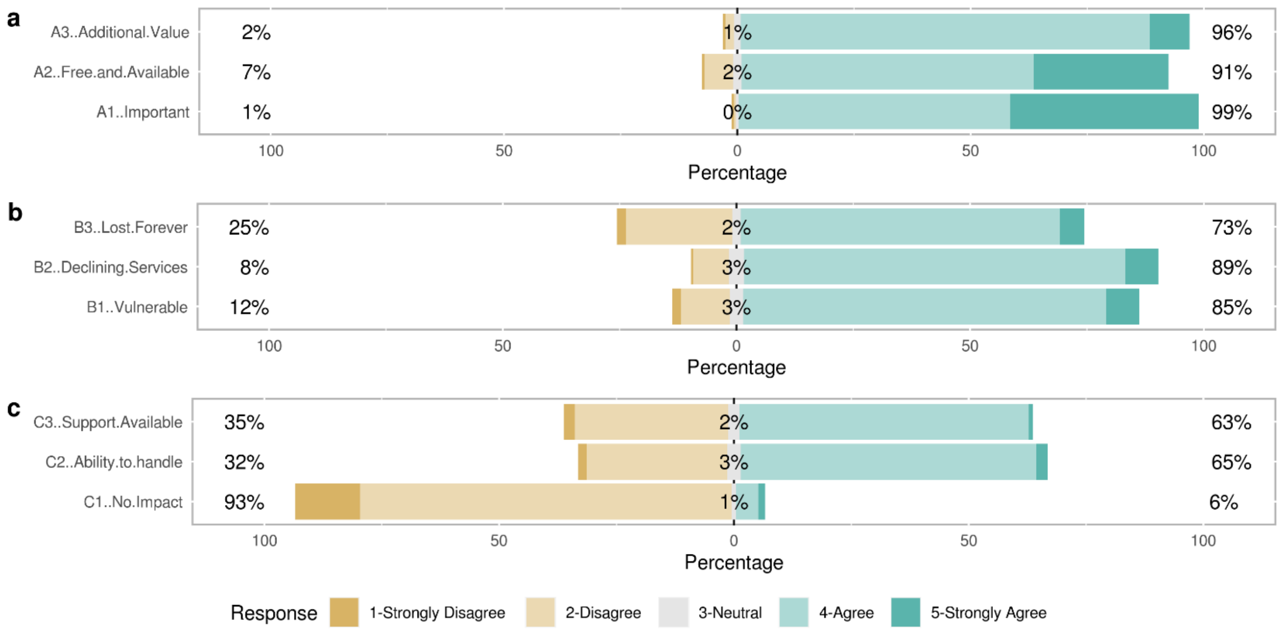

Figure 6-6 Level of agreement to various statements about the utility (a), vulnerability (b), and resilience (c) of mountain resources

**bars are centred on the neutral response; area to the left indicate negative responses (strongly disagree, disagree), whereas area to the right indicate positive responses (agree, strongly agree)*

The question about whether losing the mountain environment would have 'no impact' on the community was intentionally phrased as a double negative, in order to force respondents to think twice instead of just agreeing by default. The majority (93%) indeed disagreed or strongly disagreed with this statement. However, when asked to list the number one challenge they faced, few (<10%) listed climate change or environmental concerns. The most commonly mentioned strategies for coping were to change agricultural practices and to diversify livelihood and sources of income (Table 6-11).

Table 6-11 Principal challenges and adaptation strategies mentioned by respondents

ADAPTATION STRATEGY	Percent of Respondents	PRIMARY CHALLENGE	Percent of Respondents
Move	0%	**Employment**	**56%**
Change Food Source	9%	Politics	18%
Change Agricultural Practices	**45%**	Government Services	23%
Diversify Income	31%	Environment	9%
Change Water Supply	6%		
Appeal to Government/NGO	4%		

6.2.4.2 Adaptive capacity

Although respondents were cognizant of the changes occurring around them and the threat to their livelihoods, many felt adaptation to these changes was possible, and were optimistic about the future:

> *"The global change - this community is positive. They are able to adapt to any incoming issues, any challenges that have come. And any issue that will enable the... the challenges will change from negative to positive- they are ready. Our community are ready, and some have started - some have started planting trees." (KII #1, Mt. Elgon)*

Respondents provided an extensive list of solutions- some of which were ongoing and others were proposed (Table 6-12). These activities included sensitizations of the public on environmental stewardship, as well as a host of tree planting and rehabilitation activities. Many indicated that there was much more that could be done, and pointed to the need for more assistance from the national government and international community to fund and support local initiatives.

Table 6-12 Adaptive measures suggested by interview and focus group discussion participants

ADAPTIVE CAPACITY	Adaptation (Mitigation) Actions
Local (proposed and ongoing activities)	•planting indigenous trees, not just plantation system •teaching people to plant trees on the farm and along water courses •spotting landslide hazard areas and rehabilitating them; managing steep slope areas •establishing user rights and user groups; using these to handle disputes and bring together stakeholders •investing in afforestation, reforestation, and reclamation •promoting diversification of income •policing the forest the traditional way, learned from the elders •planting with monitoring/evaluation follow-up •rehabilitate watercourses with indigenous trees and shrubs •plant with water friendly trees and those that can naturally regenerate •use local mechanisms to store water during dry spells- dams and rationing •sensitizing people on the value of tree planting and forest protection: cut a tree, plant a tree; plant 10 trees every time you go up the mountain •increase water use efficiency- particularly in irrigation •encouraging use of solar energy •engage in information sharing and data collection •plant climate resilient crops •putting out fires as a community, allowing forest to regrow
National (proposed activities and criticisms of existing actions)	•relocate people living on steep slopes untenable for farming •support to local tree planting and conservation initiatives •provide monetary returns to the community from mountain tourism •work together with NGOs to fully protect the watershed (as they did in the Aberdares) •invest in large scale afforestation •be involved at all levels, local to international, since climate change is a shared effort •disseminate weather and climate information •sensitize on new farming methods •involve the local community in policy making
International (proposed actions)	•implement carbon compensation to make those who travel, pay for their carbon footprint •compensate villages for keeping trees •require all the countries in the Nile watershed to pitch in to protect Kenya Water Towers •climate change is an international phenomenon, it requires an international effort

The most common solutions proposed were ways to increase forest cover. Most people saw deforestation as the principal problem, and therefore the solution was to plant more trees:

> *"Meaning that [if] the government will push people away from their lands to create a larger area for Mount Kenya, things will get back to normal. Even if there is global warming, Mount Kenya only needs a big size of the forest, very protected, and the snow can get back." (FGD #2, Mt. Kenya)*

And there was a high confidence in the ability to do so and thus stem the tide of climate change:

> *"But the way that I am protecting Gathiuru and we are planting trees like they need to be, and if other stations do the same, this climate change- we will beat it! So that's why me, I*

don't fear that we will do the work that needs to be done. I'm saying this climate change won't come unless it is from God- because if it is from God then we can't fight that. But if it has to do with what we've harmed- that we can fix and we can continue to fix. We will succeed." (KII #2, Mt. Kenya)

Nevertheless, the communities also had criticisms of national policies and practices. They felt that the Plantation Establishment and Livelihood Improvement Scheme (PELIS), a government incentive system to encourage forest growth in Kenya, was not being properly implemented and was being abused. They also noted the lack of follow-up actions for tree planting operations and the fact that policies often don't consider the reality on the ground. Corruption was seen as limitation to the success of different government projects. Overall there was the sense that national government could do much more to help them adapt to climate change.

6.2.4.3 Local ownership

The importance of local ownership of the mountain was also something that came out strongly in the interviews and focus group discussions. Several individuals pointed to a long tradition of protecting the mountain, and a confidence in the ability to keep doing so:

"The mountains were being protected even before the advent of white people, they were protected. You know there was no written law, but they were protected mainly the mountains and the forests through taboos and superstitions. I think you understand what I mean. They were being feared- these taboos and superstitions- were being feared that nobody wanted to touch a tree or destroy anything where the- those people who were in charge of regulating those things are normal through what God created." (KII #3, Mt. Kenya)

And another:

"You know our traditions as the Ogiek, we don't kill- we are not allowed to kill certain animals. We don't fell trees, because we are beekeepers and when we fell the trees or burn the forest, we lose honey. So we are the caretakers of the forest in a great way. And we know water is also a source of income for our animals, they drink, and it gives us rain, so we cannot destroy the trees. So traditional knowledge is also important, and the mountain

knowledge...When you go to America to the Amazon forest, is it being take care of by the government or by the people?" (KII #2, Mt. Elgon)

Others, however, saw that some of this ownership had already been lost and suggested the need for more community control and involvement:

"So, for me, I would suggest the mountain and the forest to be fully covered- fully protected- and also the Kenya Wildlife Service should do a lot of campaigns to sensitize people, for us to have a sense of ownership [that] this mountain, this forest belongs to us. Like Mukogodo forest here, you see the community surrounding there have that feeling in their hearts- this is our forest- and in that we would protect it, and it will benefit us. But there are people who see the forest as a source of income, while they forget that forest is not a source of income, it's a source of life." (FGD #2, Mt. Kenya)

6.3 Discussion

6.3.1 Community perception and utilization of the mountains

The communities that surround Mount Kenya and Mount Elgon have a high level of interaction with the two mountains and appreciate a variety of ecosystem services from them (Figure 6-2). Most respondents did not differentiate the alpine zone from the rest of the mountain, and so services were seen as being derived from the mountain a whole. The main service that was recognized from both mountains was provision of water, but other services were equally appreciated. Communities on both mountains could point to an extensive list of services that they received from the mountain (Table 6-5), and talked enthusiastically about these services. This suggests a strong dependence of the communities on mountain resources and also a high degree of knowledge about the mountains (Elwell et al., 2020). Overall, cultural services were valued slightly less than other services (Figure 6-2), but this varied by study area (Table 6-9).

Perceptions on ecosystem services were not uniform and there was significant variation according to demographic and spatial factors. Gender, ethnicity, age, and economic status all have been shown to affect perceptions in one way or other (Chakraborty & Gasparatos, 2019; Cuni-Sanchez et al., 2016; Cuni-Sanchez et al., 2019b; Dorji et al., 2019; Mensah et al., 2017; Xun et al., 2017). This study reaffirmed such differences, but found that the influence of location perhaps dominated these other factors (Table 6-4). Overall, study area (Mount Kenya vs. Mount Elgon) was the biggest influence on perceptions (Figure 6-5). Study area incorporates a suite of factors: ethnicity, socio-economic status, and even spatial variables all vary with study area. Each study area also has a different socio-political-economic context which drives perceptions (Cuni-Sanchez et al., 2016). In general, those most dependent on the mountain for their livelihoods ranked the provisioning and cultural services of the mountains highest, whereas those further way appreciated the regulating services and of course water. People naturally are most concerned with services that directly affect them, even if sometimes there is a mismatch between awareness and importance of these services (Xun et al., 2017). These differences came out also qualitatively in the frequency and intensity of responses (Table 6-10). Mount Kenya respondents on the whole appeared to be more knowledgeable about ecosystem services, and yet more jaded about those services, ranking them on the whole lower than in Mount Elgon (Table 6-9). The higher levels of education and variety of occupations, combined with the higher levels of immigration, implied a higher degree of mobility and thus a lower direct connection to the landscape itself. These people tend to appreciate regulating services of the mountain more - climate regulation and water purification - while appreciating direct resources from the mountain less (Table 6-4).

6.3.2 Ecosystem service changes

Changes in the hydrological cycle were seen as the biggest changes in the two mountains over the lifetime of most respondents. This included changes in seasonality and rainfall formation patterns as well as the quantity and quality of available water in the streams. But changes were noticed in all the ecosystem services to varying degrees (Figure 6-3). Some of the observations, for example changes in cloud formation and hail, are details that are not easily picked up in meteorological records and yet are important indications of climate changes. A common theme was that weather patterns had become more unpredictable (Table 6-8). These observations are consistent with what has been witnessed around the world. Changes in rainfall quantity, seasonality, and pattern is a common observation around the world (Adhikari et al., 2018; Córdova et al., 2019; Cuni-Sanchez, Omeny, et al., 2019; Ksenofontov et al., 2019; Schneiderbauer et al., 2020), as is the experience that weather patterns have become unpredictable. This is particularly true for communities at the forefront of climate change, for example indigenous communities in the arctic tundra (Buijs, 2011; Cuerrier et al., 2015; Doloisio & Vanderlinden, 2020; Dowsley et al., 2011).

Cultural services and medicines had the most polarized responses, with the most ‘high change’ and ‘no change’ responses. While cultural services of the mountain were widely recognized, there was the sense that these services had changed - that the traditional knowledge involved in participating in these cultural services were being lost. Other communities around the globe that rely on traditional ecological knowledge (TEK) have also reported a cultural transition underway (Buijs, 2011; Oteros-Rozas et al., 2013). This view was not uniform, however, with some still strongly feeling the cultural value of the mountain, whereas others seeing it as just a service their forefathers had used.

There was no clear pattern of views on changes according to demographic or spatial factors (Table 6-7). Farmers tended to rank changes higher which would make sense as they depend more on these services for their daily livelihoods. Interestingly though, some of those more removed from the mountain ranked changes in ecosystem services higher. Perhaps those that interact with those services on a daily basis, have a harder time identifying changes as they are occurring incrementally each day, and so they may habituate to those changes without realizing it. Guides, however, benefit from being constant repeat visitors, intimately familiar with the area but with the benefit of not being habituated to the changes around them.

Some of the most detailed changes were noted by the guides, who were able to pinpoint rather specific changes in vegetation, wildlife, and climate patterns- and they often had specific benchmarks for comparison. Mountain guides are a unique type of civilian scientist: their job requires them to be frequent visitors of these remote areas where there are few meteorological or ecological records. In addition, their job requires them to be close observers of the climate, as they are responsible for the safety of their clients, and abrupt changes in weather can be incredibly dangerous for hikers. Mountain guides around the world have been able to document climate changes to a degree not seen in other parts of the world. Hiking routes have become too hazardous and weather pattern changes have forced them to change the seasonality of their work in certain parts of the world (Mourey et al., 2020; Purdie & Kerr, 2018; Salim et al., 2019). These are similar to the observations seen by the guides in Mount Kenya. The guides also were able to notice very detailed changes in vegetation, soil, air, and water that may not have been noticeable to other mountain communities (see Chapter 7). Enlisting citizens in the collection of scientific data is a useful approach, particularly when the research question is so broad and the amount of data so vast that conventional means of data collection are inadequate for the task (Bonney et al., 2009, 2016). This is the case with climate change. The communities surrounding Mount Kenya and Mount Elgon have a close connection to the landscape (Figure 6-1) and a vested interest in understanding the impacts of climate change. This makes them ideal citizen scientists. Using knowledge handed down from their forefathers, they have an idea of what patterns to expect from the mountain, and therefore have some basis for observing changes in the mountain.

For many respondents, changes witnessed in the environment were seen primarily as a local phenomenon and not necessarily a global phenomenon. Loss of various tree species, wildlife species and topsoil was often associated with deforestation and land degradation (Appendix C3). Others saw the changes as a mystery- something caused by God. Other studies too have noted this uncertainty in the attribution of climate change (Buijs, 2011; Cuni-Sanchez et al., 2019a; Ksenofontov et al., 2019; Schneiderbauer et al., 2020). The link forests and climate came out strongly in the qualitative data. Forests were seen as bringing the rain, and therefore the loss of the forests meant loss of rain. This theory, in the academic world, has been called the 'Biotic Pump' theory- that forest masses draw in moist air from the oceans causing precipitation over forests. While this is an attractive theory, and there is growing evidence to suggest that forests play a role in the hydrological cycle through transpiration and cloud interception (Bagley et al., 2014; Makarieva & Gorshkov, 2007; Sheil, 2018; Spracklen et al., 2012; Zemp et al., 2017), there is also significant debate surrounding this theory (Bruijnzeel, 2004; Meesters et al., 2009). It does not account for the role of sea-surface temperature anomalies and orographic effects which are so important in shaping atmospheric conditions (Bruijnzeel, 2004).

The cultural connection to the mountain was seen as an important factor in both mountains, though the loss of cultural services was more noticed in Mount Kenya. Cultural connection to a landscape can support communities in the face of a changing environment. This has been termed 'cultural resilience' and is an important element of adaptation to climate change (Davies & Moore, 2016). The adaptive capacity of a community depends on their ability to recognize and value ecosystem services and document changes in those services, and then come up with strategies to cope in the face of these changes (Anderson & Bollig, 2016; Davies & Moore, 2016; Straight et al., 2016). Respondents on both mountains, but particularly Mount Elgon, demonstrated such an awareness and this has enabled them to be optimistic in the face of climate change (Figure 6-6). These communities also demonstrated a keen understanding of the threat of climate change and had robust ideas for addressing these changes (Table 6-12).

6.4 Summary

Local communities are the best situated to document climate changes in remote areas as they interact with these environments on a daily basis. The communities around Mount Kenya and Mount Elgon demonstrated a high appreciation of mountain ecosystem services and a detailed understanding of changes in those services. Water was the service seen as the most important coming from the mountains, and also the one for which the largest amount of change had been seen. In particular, the increasing unpredictability of weather patterns was seen as a challenge. The communities demonstrated a cultural connection to the landscape, but there were also signs of a cultural transition underway with some of the significance of the mountains being lost on the newer generations. For the most part, however, communities were confident in their ability to deal with these changes, mostly due to a sense of pride and ownership of the mountains and a familiarity with the landscape, suggesting a type of cultural resilience. Those who interacted with the mountain more generally had a higher appreciation of ecosystem services (particularly cultural services) and were therefore less concerned about climate changes and their ability to cope.

Chapter 7 SYNTHESIS, CONCLUSIONS, AND RECOMMENDATIONS

7.1 Introduction

This study has looked at the impacts of recent climate change on biotic and abiotic patterns in the afroalpine areas of Kenya, as well as the effects on downstream communities. The research examined two specific areas at the tops of Mount Elgon and Mount Kenya- the Koitobos and Teleki valleys - to explore impacts on the biophysical environment, and then examined socio-economic effects on the communities surrounding the two mountains. The research has therefore dealt in nested scales: biophysical processes on the mountain were examined at the microscale, whereas socioeconomic processes were examined at the macroscale. Patterns and trends were the organizing principles of this research. Landscape patterns determine and are determined by underlying ecological processes (Hessburg et al., 1999); by understanding trends in patterns, one can better understand underlying processes. In this study, the patterns with respect to temperature and precipitation cycles reflect underlying meteorological processes with respect to wind, pressure, and radiation. These patterns determine temperature and moisture dynamics, which affect the distribution and diversity of plant communities. These, in turn, contribute to the water and carbon cycles, and thus the ecosystem services that the mountains provide, which finally influences the pattern of human interactions with the mountains. Thus there is a cascading flow of phenomena in nested scales.

The patterns of Afro-alpine climate, ecology, and society are characterized by great temporal and spatial variability. Chapter 4 has shown how climate patterns vary spatially according to elevation (lapse rates) and mountain aspect (orography), and temporally by day (freeze-thaw cycle) and by year (seasonality). Chapter 5 has shown how vegetation patterns vary by elevation and valley position, and are also influenced by interactions with other plant communities. The growth form and life history traits of the different species in the area are adaptations to the unique climatic conditions. Chapter 6 has shown how demographics, location, and socio-cultural situation all influence patterns of interaction with the mountains and perceptions of ecosystems services and climate change.

7.2 Vulnerability

The IPCC AR6 report views climate change, human society, and ecosystems as inextricably linked. Climate change directly affects both society and ecosystems depending on the vulnerability of those systems (IPCC, 2022b). The alpine ecosystems in Kenya illustrate the interplay between these three factors, and as such, can be seen as a microcosm of these global systems. The degree to which climate change is impacting the alpine zones of Kenya determines their vulnerability. This is a function of exposure to climate change, sensitivity to that change, and adaptive capacity (Adger, 2006; IPCC, 2022b). There is both a biophysical and a socio-economic element to this vulnerability (Füssel, 2007).

7.2.1 Biophysical vulnerability

The climate data investigated in this study suggest that exposure to climate change is high in the mountains of Kenya - even if perhaps not quite as high as the models predict. There is evidence of warming from multiple datasets- reanalysis datasets, in-situ data loggers, and local observations. While it is true that the ground station data does not support this finding (Figure 4-6), there is reason to suspect these trends given the repeated alterations to the sensors over the course of the time series. The majority of the evidence points towards continuous warming over the past half century. The temperature trends for both study area valleys was strongly positive (Figure 4-1), amounting to roughly 1.5 °C over the 60 year period or 0.24 - 0.28 °C/decade. At Met Station in Mount Kenya, the temperature trend shown as a departure from the baseline (1961-1990) amounted to a warming of 0.24 °C/decade (Figure 4-7). As compared to historical point measurements, absolute minimum temperatures (which are generally the more reliable measurements) were found to be some 3-5 °C higher than in historical records from the 1950s-1980s (Table 4-10). These values are consistent with IPCC observations and predictions for mountain areas around the world (IPCC), but not quite the level of warming predicted by the models for tropical alpine areas of 0.4 to 0.45 °C/decade (Anthelme et al., 2014).

The precipitation trends also suggest high exposure, although not as directly as for temperature. Both valleys showed no trend in monthly precipitation (Figure 4-2), and there were no significant seasonal differences either at Met Station when comparing the last 20 years (2000 – 2020) to the 20 years before (1980 – 2000) (Figure 4-11). At base of mountain, however, there were negative trends for most stations - either for total precipitation or seasonal precipitation (Table 4-3). Similarly for streamflow, the gauge stations around both mountains displayed largely negative trends (Table 4-5; Table 4-6). The A3 station, which was the highest elevation station studies and largely unaffected by land-use changes, displayed considerable variability in recent years with more extreme flows alongside declining baseflow (Figure 4-14; 4-15; 4-16). This is in keeping with the IPCC's prediction for high mountains of no overall trend in precipitation the mountains, but a high confidence of changing precipitation and discharge patterns in the low lowlands surrounding the mountains. This creates for more extremes - increases in the frequency and severity of floods and droughts - and in the long-term, to large declines in baseflow (IPCC, 2022b).

Vegetation trends point to the sensitivity of the system to these changes. Overall species diversity was significantly lower in 2021 as compared to 1980 (Figure 5-2; 5-3), and this was associated with declines/disappearances of a number of species (Table 5-2). Species shifting were also documented, although in both directions- both up-slope and down-slope (Table 5-3; Figure 5-4). These findings are in contrast to the IPCC general finding of increasing species diversity in the higher elevations as species move up-slope in response to warming, though declines are predicted in the longer term, as species run out of space to migrate to (IPCC, 2022a). The changes in *D. keniodendron* demography also point to sensitivity in alpine ecology. One would expect the old individuals to be the most resilient to changes, and yet these are the ones that appear to be dying (Figure 5-8). *Dendrosenecio keniodendron* is the most conspicuous species in the valley and likely functions as a keystone species and habitat modifier. It is one of the main determinants of plant community structure (Table 5-8). Changes in this species may, therefore, have compounding effects on the rest of the plants in the valley. There is also the possibility of thresholds and tipping points (Monaco & Helmuth, 2011): perhaps initially *D. keniodendron* has been able to buffer other species from the impacts of climate change, but once it disappears the ecosystem will undergo rapid change.

7.2.2 Socioeconomic vulnerability

The degree then to which changes in biophysical processes are felt by the surrounding communities, determines the socioeconomic vulnerability. This again is a function of exposure and sensitivity. The communities around Mount Elgon and Mount Kenya indicated that they relied on mountain resources and valued the ecosystem services of the mountains highly. They noted that if those services were not there, the impact on their livelihoods would be drastic (Figure 6-6). In Mount Elgon, the provisioning services were particularly valued, whereas in Mount Kenya there was more reliance on the financial benefits that came from tourism. In both areas, regulating services were appreciated as well as cultural services to a lesser extent (Table 6-9; Figure 6-2).

Ecosystem services were also seen to have changed in both mountains. The service to have changed the most was rainfall (Table 6-6; Table 6-8), which was seen to have changed both by quantity and pattern. But high levels of change (mostly declines) were observed in most services (Figure 6-3), with the largest changes seen in cultural heritage, raw material supply and food production. This suggests a high level of exposure to changes in the environment, and is in keeping with the IPCC findings of declines in ecosystem services and particularly cultural resources (IPCC, 2022c) .

The sensitivity of mountain communities to changes in ecosystem services is a little less clear. While the communities agreed to statements about vulnerability, they also remained fairly optimistic for the future. Very few listed environmental concerns as their number one challenge, suggesting it was not seen as an existential threat (Table 6-11). The IPCC, however, suggests that mountain communities will be particularly vulnerable to climate change as they are sensitive to small disruptions to their livelihoods and have few options for adaptation (IPCC, 2022b). As with the biophysical environment then, there remains questions as to the sensitivity of the system, and whether there are thresholds, feedbacks, or cascading effects that can compound the impacts of climate change in these regions.

7.2.3 Resilience and adaptive capacity

In the mountains of Kenya, both the biophysical and socioeconomic environments were seen to be exposed and sensitive to climate change. However, in both cases, the overall vulnerability was perhaps lower than expected. This suggests that there is a resilience or adaptive capacity in these systems that allows a degree of resistance to change.

In Mount Kenya, although there were significant changes in the plant communities in Teleki valley in terms of diversity, perhaps what was most remarkable was the overall stability of the system. The most dominant species showed little change in abundance or distribution across the valley (Table 5-5; Table 5-6). While there were suggestions of shifts by valley position and elevation for the Senecios, there were no significant differences between the two time periods (Table 5-6). There is likely a built-in resilience in these plant communities as they are adapted to harsh environments. The climate of the area forces species to be able to tolerate a freeze/thaw on a daily basis, high levels of radiation, low humidity, and occasional intense wind and precipitation events. Once these species have become established, therefore, they are able to tolerate a wide range of environmental conditions (Paniw et al., 2018; Smith & Young, 1987).

There are also hints of an inherent resilience in the human communities surrounding the mountains. Most respondents indicated that they had the ability to handle changes in the future and had the support that they needed to survive (Figure 6-6). They acknowledged the threat of climate change but appeared confident in their ability to cope. This can be seen as a type of cultural resilience, which is a function of attitudes, traditions, and beliefs. Particularly in Mount Elgon, there seemed to be a strong cultural connection to the landscape which provides the communities with the tools needed to cope. This resilience can be seen as part of the adaptive capacity of the communities. These are actions or factors that can ameliorate the sensitivity of the community to climate changes (Adger, 2006). Both communities had valuable suggestions for how to deal with climate change, and an awareness of the national and international scope of the problem. While adaptive capacity is often framed in terms of access to resources and power (Abdul-Razak & Kruse, 2017; Choden et al., 2020), which this study did not address, attitudes and perceptions are also important aspects of adaptive capacity.

7.3 Transdisciplinarity

7.3.1 Transdisciplinarity and co-production of knowledge

Climate change has been termed a 'wicked' problem due to the incredible complexity surrounding the issue (Head, 2008; Rittel & Webber, 1973). One thing that makes climate change such a wicked problem is the levels of complexity, which include generative, dynamic and social complexity (Kahane, 2004). This just means that the problem is new and unfamiliar, it is always changing, and there are many different personalities and opinions at work. There is no blueprint to fall back on and there is no linearity in causes and effects. The paradigm of Trans-Disciplinary Research (TDR) has come to the fore as the only way to address such a problem. TDR breaks down the traditional boundaries between disciplines, and considers the interplay among disciplines within the greater societal context (Klenk & Meehan, 2015; Max-Neef, 2005). One keystone of Trans-Disciplinary Research, particularly in the context of climate change, is the incorporation of local knowledge. This presupposes that the traditional scientific modes of understanding will necessarily fall short in capturing climate change impacts, and that only with local knowledge can the full picture be gained. Local observations provide a level of detail that is lacking in model outputs, and they can help prioritize these impacts as they focus on the ones of most importance to the communities themselves (Reyes-García et al., 2019; Savo et al., 2016).

In this study, mountain guides were seen as valuable sources of knowledge for these remote environments. They have the perfect background for it, as their job requires them to be very observant of their surroundings. Their livelihood depends on being able to read their environment well, both for safety and because their clients generally expect to be kept informed of the area. What's more, mountain guides are frequent visitors to these hard-to-reach areas, and many have been guiding for decades. They are, therefore, are a critical information source to an area that otherwise has very little data and almost no permanent records. There has been consistency in observations of mountain guides around the world, who have documented changes in weather patterns and species ranges. In particular, guides have noted how the unpredictability of weather has increased the hazards in their line of work (Mourey et al., 2020; Purdie & Kerr, 2018; Salim et al., 2019).

7.3.2 Comparison of perceived changes with meteorological and survey records

The guides in Mount Kenya had several observations when it came to changes in climate and ecology of the mountain. Many of these are consistent with model predictions, but there were some differences. A summary of all these changes is given in Table 7-1 (for more details see Appendix C3). There was general consensus that temperatures are warming, that precipitation patterns are changing, that there are shifts in vegetation and species mortality, and that overall ecosystem services have declined. Where the current study and local observations differ the most from model predictions is for soil and vegetation. Here the indications from this study are more cryptic, suggesting a variety of possible responses to the climate change signal.

Table 7-1 Summary of changes observed in this study as compared to local observations and predictions from the IPCC

Parameter	Current Study	Local Observations	IPCC Predictions
Temperature	Monotonic increase in mean and minimum temperatures from reanalysis data and hobo data (decline in mean temperatures from ground station data)	Warming temperatures in the day, but colder temperatures at night. Loss of ice and snow on the mountain	Temperature increases and associated impacts on ice melting and permafrost thawing
Precipitation	On the mountain no change in either total precipitation or seasonality, but at the base significant declines in total precipitation and signs of changing seasonality	Decline in precipitation, changing rainfall patterns, increasing and unpredictability	Changing runoff patterns on the mountain, leading to increasing variability in streamflow and long-term declines in baseflow
Vegetation	Few significant changes in plant distribution, suggestions of both upward and downward movements; suggestions of species disappearances; mortality of older Senecios and increase in juveniles	Plants moving both up wards and downwards in elevation; mortality of giant rosettes; appearance of new plants, faster growth of plants higher up on the mountain	Upslope movements of species leading to increasing diversity in the alpine zone, but also extinction of certain cold-adapted species
Soil	No significant changes in soil chemical properties	Soil becoming more stable, less movements through the process of solifluction	Soil becoming less stable leading to higher risk of landslides
Ecosystem Services	Changes (mostly negative) in almost all ecosystem services- provisioning, regulating, and cultural. Largest changes in provisioning and cultural services		Large changes in cultural services of the mountain particularly tourism and recreation

(IPCC, 2022c)

Inherent in the transdisciplinary process is the iterative nature of investigation: local observations lead to questions, which are investigated deductively and then fed back through the lens of local knowledge to generate more questions. Unfortunately, it was beyond the scope of this study to carry this type of investigation out in full, but the observations in this study do generate important questions for the future.

7.3.3 Co-produced research questions

Several research questions have emerged from this study, based on local observations. With regard to temperature, there was the interesting observation that temperatures had not only become warmer, but at the same time had become colder at night:

"I think the temperature has changed both ways. In the day, you feel like it's a little bit hotter than it used to be, and at night being more colder - you tend to see more open sky at night than it used to be. And obviously, when it's open sky, it's always very cold at night. So I see it both ways- during the day a little bit hotter, at night a little bit colder" (KII #1, Mt. Kenya)

Whereas the warming documented in the study showed a steady increase for both minimum and maximum temperatures, this observation suggests that there may be other factors involved. The perceived cooler temperatures could be more a function of humidity and wind changes which can make a day feel colder than it actually is (Schoen, 2005). This is an important factor when considering biological sensitivity to climate change.

Among the guides there was a strong consensus that weather patterns had changed - both daily and seasonally - up on the mountains:

"[Previously] we knew that if you moved from one camp to the other, you leave early then you're ok- you won't be rained on, because it will rain in the afternoon. These days, things have changed, it can rain at night, it can rain in the morning….what I would say is I cannot plan what I'm doing on the mountain, looking at the seasons that used to be there: totally destabilized. When you think it won't rain, it rains, when you think it will rain it doesn't rain." (KII #1, Mt. Kenya)

This is another observation that warrants further study. While overall precipitation patterns on the mountain showed no trend according to TerraClimate, that dataset has too coarse of a resolution to quantify the types of changes that the guides have noted. Changes in daily moisture patterns will have an important influence on biotic responses to climate change, particularly as morphological adaptations of these plants are as much a response to aridity as to cold temperatures (Rundel et al., 1994).

The guides also anticipated the finding of plants shifting in both directions. They had observed both upward and downwards shifts in elevation:

"Another thing, I have seen like funny-funny plants coming up. Like, I was in Letudo last week and you realize pine trees are naturally germinating in the mountain at nearly 4000 meters. And it's funny to see a pine tree just growing there." *(FGD #1, Mt. Kenya)*

"And also there are plants from up there that are now coming lower. I have noticed a heath- huge heath plant- here at below Chukuzilia just here, and in the side of the forest- a huge one. Yeah, and it's something like I couldn't expect to be there." (FGD #1, Mt. Kenya)

More research is needed on these shifts and what drives certain plants to shift upward or downward. It is hypothesized in this study that conflicting pressures of temperature and aridity partially explain these shifts. It would be interesting to see if there are certain life-forms that are more susceptible to these pressures (Hedberg, 1970; Sklenář et al., 2016).

There was also the observation of plant species turnover. Certain species were seen to be dying off, whereas others were coming in:

"I am realizing that we have come to that point whereby plants like Senecios *and* Lobelias *are now starting to die. The ones I remember, going up Mackinders sides were huge, and I think must be going to the maximum. And now they're starting to fall over. So a place that used to be like a forest is no more- you can see through." (KII #1, Mt. Kenya)*

"The one thing that I saw- I think in January last year - there's a plant - I don't know its name in English....I was surprised because I've never seen it before on the mountain." (KII #1, Mt. Kenya)

The current survey also pointed to the possibility of plants dying off in Teleki Valley. Particularly for the case of *D. keniodendron*, there were much fewer of the older, larger individuals recorded in 2021 as compared to 1980. The decrease in diversity and abundance of the majority of the species also suggests mortality. However, there are no indications of new species colonizing Teleki Valley. This would be an interesting finding as elsewhere there are indications that climate change can reduce resilience to new species invasions (Schuchardt et al., 2023).

There were also observations specific to the giant Senecios - that they were blooming more frequently and growing faster:

> *"In the books, they say there are those alpine [species] like the giant groundsels that will bloom like after a decade. And for me, I have seen them bloom in like months [or] after several years. So in the book, it says it will take seven years to bloom, but for me since I started 11 years now, I have seen a couple of them." (FGD #1, Mt. Kenya)*

> *"When we started mountaineering and talking about* Senecios *and* Lobelias *staying for years, like 50 years, before it will flower. But now I think that is becoming faster. Because I've seen a few, I remember I saw this plant in this area...and two years later, you find it, and it has grown faster than they used to....obviously a sign of things getting better there- weather getting warmer." (KII #1, Mt. Kenya)*

Changes in growth rates and reproduction is consistent with climate change predictions (IPCC, 2022a; Körner, 2005; Paniw et al., 2018). In this study, the biggest indication of these process at play was the change in population structure for *D. keniodendron*, which was accompanied by perhaps a lower incidence of forking. But more observations would be needed to document flowering frequency and growth rates of *D. keniodendron*. There are surprisingly few studies quantifying these processes, and much of what is known is just from incidental observations. A study from 1980s suggest growth rates for *D. keniodendron* of around 3-6 cm/yr. depending on the reproductive status (Beck et al., 1984).

Finally, there was the observation was that the soil was becoming more stable:

> *"I think the main thing for me is the soil is getting more stable now, than before. And as I said that could be because there's less rainfall maybe, because whenever the rains start, things just come down...It's more stabilized soil and because of that, more plants growing there; before that was not happening because the soil was moving all the time." (KII #1, Mt. Kenya)*

The observation that soil has become more stable is counter to model predictions of increased destabilization of mountain slopes (IPCC, 2022c). However, tropical mountains undergo a unique process known as solifluction. Solifluction refers to the suite of soil phenomenon associated with this freeze/thaw cycle on a daily basis: these include soil movements and patterns that occur when ice-crystals form and thaw in the soil each day (Hedberg, 1964). Warming temperatures may lead to a decline in this process, thus enhancing stability. Indeed another guide indicated that this has already happened:

> *"[Solifluction] is happening, but very rarely. It's not as how it used to be earlier before. Because many years before, or when I started, even if at night - maybe if someone is ahead of me heading to the summit - I would be able to see his footprints everywhere. But these days, if you don't know the trail, no footprints will be left." (FGD #1, Mt. Kenya)*

A decline in solifluction also could have implications on soil properties, as it would imply a decline in physical weathering of the soil, even as enhanced microbial activity from warming temperatures would imply an increase in chemical weathering. All of this would have important impacts on biological communities (Coe, 1967; Gütlein et al., 2017; Ma & Chang, 2019).

7.4 Conclusions

Tropical alpine ecosystems are unique and important ecosystems that are threatened by climate change. These special ecosystems are at the forefront of climate change and may experience the impacts of warming before other areas. Moreover, being mountains near the equator, the range of climatic and ecological conditions on a single mountain are analogous to the range of conditions stretching from the equator to the poles. It has been said that one degree of latitude is roughly equivalent to 200 m elevation gain (Montgomery, 2006). This makes tropical alpine areas the ideal setting to investigate climate change. These ecosystems can act as the figurative 'canary in the coal mine'- some of the first terrestrial ecosystems to feel the impact of climate change, and ones that are likely sensitive to that warming. How these systems react to climate change can be an indication of potential responses in the rest of the globe.

This study has examined the climate, ecology, and human society for the tropical alpine regions of Kenya, providing a holistic look at climate change in these regions, and hopefully paving the way for future studies and a renewed interest in these important and fascinating ecosystems. The biophysical environment in the alpine zones of Kenya is changing but there is uncertainty as to the amount of change, and it may be changing less than often is assumed. Results point to inertia in the system as well as response variability. The impact on communities is already being felt, but again there is variability in how these impacts are felt, and there is the suggestion of underlying resilience.

Climate trends and patterns were investigated on both mountains. Overall there is indication that temperature has warmed consistently over the past 60 years in the alpine zones of both mountains. Minimum temperatures have increased as well as mean temperatures, and potentially even more so. There has been no significant changes in precipitation in the alpine zones of either mountain, but in the lower elevations of Mount Kenya there are indications of declines in precipitation amounts and changes in seasonality. Streamflow coming off the mountains has changed significantly, and in Mount Kenya base flow has declined whereas peak flows have become more variable.

With respect to vegetation patterns on the mountains, little could be said about Mount Elgon due to the lack of a baseline dataset, but in the alpine zone of Mount Kenya there was little significant change in abundance and distribution of the dominant species. The changes that were discernable were sometimes conflicting, suggesting both upward and downward shifts in elevation are occurring. Species diversity has also likely declined, which is contrary to previous studies suggesting increases in diversity due to the movement of species upward in response to climate change. For the distinctive *Dendrosenecion keniodendron* species there were interesting changes in demography apparent, suggesting some complex responses to climate change that are not fully understood.

Finally the human dimension to climate change in the alpine region of Kenya was investigated. Communities surrounding both mountains had a high appreciation of mountain ecosystem services which they relied on for their daily livelihoods. Provisioning services were appreciated the most- particularly water, but regulating and cultural services were also highly valued. Communities had all noticed changes in ecosystem services, mostly declines in service delivery. Again water was the service for which they had noticed the largest changes- in particular changes in seasonality and an increasing unpredictability of weather patterns. Cultural services were also appreciated and some communities had a close cultural connection to the landscape- particularly in Mount Elgon, whereas others expressed disconnect. Most people understood the threat of climate change, but few listed it as their number one concern, and most felt optimistic about their ability to handle changes in the future.

7.5 Recommendations

7.5.1 Recommendations for future study

This study has attempted to be a transdiscplinary study, examining several facets of climate change in the alpine regions of Kenya and the impacts on surrounding communities. The disciplines of meteorology, botany, soil science, ecology, history, and anthropology are brought to bear to understand this phenomenon. The two valleys on Mount Kenya and Mount Elgon have served as physical case studies in which to investigate the impacts of climate change. As humans do not live in these areas, the changes seen can be more directly linked to a global climate change phenomena rather than local anthropogenic affects (although human visitation is a factor).

The exploratory investigation into the biotic and abiotic environment of the two valleys has raised some important research questions that need to be studied in more depth. Although these questions are raised specifically for Teleki valley, the same questions also exist for Koitobos valley and the analogous plant communities found there.

- Species Diversity: Has climate change indeed led to reduced species diversity in the alpine regions? Is this decline due to local extinctions, or an increase in certain species at the expense of others? Are there new species that have established a foothold in the valley? To what extent are these thermal refugia utilized plants to persist in place despite changing temperatures?
- Elevation Shifts: What are the specific drivers of plant elevation shifts? Is it moisture or temperature or is there another factor? What specific climatic parameter are they responding to- maximums or minimums – and how does the spatial and temporal variability affect plant responses?
- Facilitation: To what extent does *D. keniodendron* serve as a habitat modifier? Is the effect mostly a facilitating effect or a competitive effect? Which life forms are most affected by *D. keniodendron* presence?
- Life History Traits: Has the reproductive strategy - semelparity and iteroparity- of the giant rosettes changed due to climate change? Given that these traits vary according to abiotic gradients, will climate changes force an evolutionary shift in these species?

- Soil processes: How does temperature change affect soil processes in the alpine zone? Has solfluction and the rate of physical or chemical weathering changed and what is the impact on biologically important soil properties?

The two mountains investigated in this study are the source for a suite of ecosystem services that communities depend on. How these services are perceived seems to vary by spatial and demographic factors. Here also there are important research questions:

- Factors shaping perceptions: Given that ethnicity, location, and distance to roads were too closely connected in this study to separate, which factor is the principal driving force shaping perceptions? Why does this factor shape perceptions and does it hold true elsewhere as well?
- Attribution of climate change: To what extent does the attribution of changes affect how problems are perceived? Whether climate changes are viewed as a local phenomenon or a global phenomenon, does this affect how people cope with the change?
- Cultural resilience: Is ‘cultural resilience’ something that can be measured? What metrics could be used to characterize an areas cultural resilience and how can this be incorporated in vulnerability indices?

7.5.2 Policy recommendations

This research also has implications for policy and management. While the study has been exploratory with few definitive findings, some of the trends seen are important enough to warrant action. Climate change obviously is already occurring, and mitigating climate change in the alpine zones of Kenya is beyond the scope of what local and national agencies can achieve. However there are policies and management practices that can enhance adaptability to these changes and limit compounding and cascading effects.

First and foremost, more monitoring is desperately needed. The lack of robust long-term datasets in alpine regions of Africa is limiting the understanding of climate change in these regions. As this study found, even in one of the most data-rich sites- the western slope of Mount Kenya - data is still sparse and there are data gaps and inconsistence in the data. Particularly disturbing is the behaviour of meteorological station data, which strongly suggest error or malfunction. These stations need to be maintained and calibrated routinely and populated with metadata. The data also needs to be made available to all easily and without cost. Secondly, more ground stations need to be put in place. Tropical alpine areas have some of the lowest densities of meteorological stations in the world (Mountain Research Initiative, 2015), and yet the complex topography in these areas requires a high density to capture the full range of conditions. Monitoring should not just be limited to temperature and precipitation but should include soil moisture, humidity, wind, and many more important parameters.

More ecological studies are also needed to address the gap in vegetation knowledge in these sensitive areas. To start with, more historic studies need to be revisited, as was done in this study- archival research can be a valuable source of information in these unique ecosystems. In addition, new long-term vegetation monitoring studies are needed. To ensure consistency and allow for comparative studies, these ecological studies should follow the methodology of the GLORIA programme (Global Observation Research Initiative in Alpine Environments) which has been validated in alpine areas around the world (Pauli et al., 2005). Finally, citizen science needs to be employed (Bonney et al., 2009). The research questions are too vast to be handled through conventional scientific projects alone. Mountain guides are frequent and repeat visitors to these remote areas and with an eye for detail; it makes sense to make use of this network. Guides can be tasked with collecting simple data on climate and ecology each time they climb the mountain in order to get real-time information on changes as they occur.

Besides monitoring and research, more can be done at the local and national level to protect these mountains and build adaptive capacity of the surrounding communities. The recommendations of the respondents in this study should be taken seriously- recommendations to enhance local capacity for environmental stewardship and foster a sense of ownership of the mountains. More can be done at the national level to enhance interaction and pride with the mountains. Education and sensitizations surrounding the importance of mountains and the alpine zone can be undertaken regularly, allowing further appreciation of ecosystem services. Furthermore cultural interaction with the mountain as well as renewed understanding of the old ways of managing mountain resources should be encouraged. Conservation of the mountain is important in order to mitigate compounding factors such as land-use change, pollution, and environmental degradation that can further contribute to ecosystem service loss in these vulnerable areas. While people should be encouraged to visit and recreate in the mountains, extractive use should be limited, and policies surrounding touristic use should be enforced. Special care should be taken to limit anthropogenic fire and resource removal, particularly in the alpine area which is very sensitive to disturbance. Finally, adaptive capacity can be enhanced for the surrounding communities by promoting local institutions such as the resource users associations - the Water Resources Users Associations and the Community Forest Associations. These have a strong role to play in empowering environmental stewardship at the local level. Furthermore all capital assets at the community level should be strengthened: financial, social capital, physical, human, and natural. These will enable communities to enhance their adaptive capacity and thus lower sensitivity to changes in the biophysical environment which are sure to occur due to climate change despite all efforts to mitigate against these changes.

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APPENDICES

APPENDIX A: Analytical Rationale

A1 Climate Analysis

A1.1 Reanalysis Datasets

There are several reanalysis datasets that cover the globe. They are designed for different purposes and each has strengths and weaknesses. The Famine Early Warning System Network (FEWS-NET) Climate Engine (https://app.climateengine.com/climateEngine), allows downloading climate data from a variety of different reanalysis datasets for a specified geographic area and time period. Three reanalysis datasets were compared in this study, but ultimately TerraClimate was deemed the best choice, with the best combination of accuracy, coverage, and resolution.

The Climate Forecast System Reanalysis (CFSR) was one of the first reanalysis datasets produced using satellite imagery and climate models and covering the globe (https://rda.ucar.edu/). The purpose of CFSR was to create a long-term historical dataset, calibrated with actual station data that included components for land, ocean, and atmosphere. It originally ran from 1979 to 2014 and covered the majority of the globe at a good spatial (38 km) and temporal resolution (6 hour or better). The dataset includes temperature, precipitation, wind speed, relative humidity and solar radiation (Saha et al., 2010). A newer version of CFSR came out in 2011 with a slightly different algorithm, and unfortunately that creates for an anomaly in the data (Barnson & Tippet, 2012).

TerraClimate is a newer dataset that provides data on temperature, precipitation, and evapo-transpiration, and runoff (Abatzoglou et al., 2018). It is actually a combination of two other reanalysis datasets: WorldClim and CRU (Climate Research Unit). It gets its high spatial resolution from WorldClim and high temporal resolution from CRU (Abatzoglou et al., 2018). WorldCim has been shown to have a light positive elevation bias particularly in the tropics, causing for inflated readings at higher elevations (Hijmans et al., 2005).

ERA5 comes from the European Centre for Medium-Range Weather Forecasts (ECMWF), as their reanalysis product version 5. It also covers the period since 1979, but work is currently underway to extend its coverage back to 1950. It has a spatial resolution of 31 km and an hourly temporal resolution. The temperature values reported are specified as 2 m air temperature values- not ground/surface values (Hersback et al., 2010). There is a further modification of the ERA5 product called ERA5_Ag which provides a suite of agro-meteorological indicators at a coarser temporal resolution (daily), but extrapolated to a finer spatial resolution (9.6km) (ECMWF, 2022). ERA5 is also the basis for the CHIRTS dataset (Climate Hazards Group InfraRed Temperature with Station-CHIRTS) which is used widely alongside the Precipitation dataset CHIRPS (Verdin et al., 2020).

A comparison of these three datasets at Met Station shows that there is general agreement in temperature ranges, but mean temperatures vary by 1-2° C. Each reanalysis dataset is based on different algorithms and different underlying assumptions. Presumably they all utilize the Met Station itself for calibration, and Met Station itself is not immune to errors (Figure A2-1). CFSR displays an abrupt shift at 2011, which is likely due to a new version of the reanalysis product that was released that year (Barnson & Tippet, 2012).

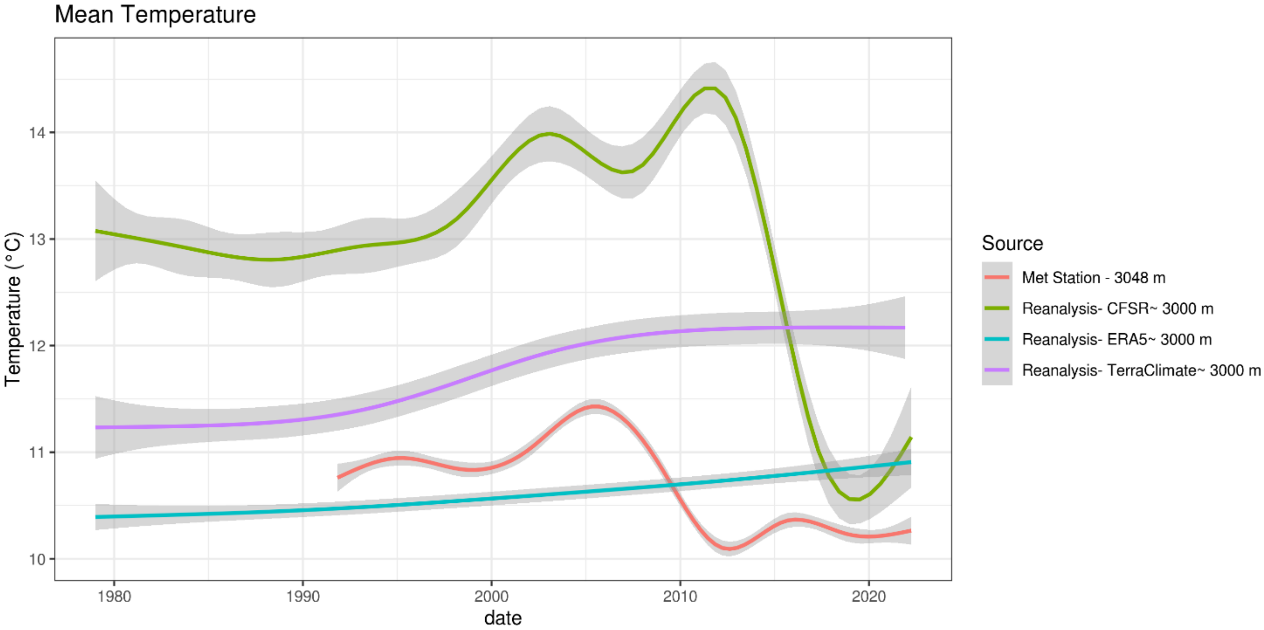

Figure A1-1 Comparison of reanalysis datasets at Met Station

Temperature summaries over the year 2021- 2022, shows the variation in monthly minimum, maximum, and mean temperatures for the different data sources. After the CFSR correction, CFSR is most closely aligned with the Met Station data, although ERA5_Ag has the best agreement with the hobo logger data (Table 4.5).

Table A1-1 Comparison of temperature datasets at the Naro Moru Meteorological Station of Mount Kenya ~3000m; March 2021- March 2022. (Temperatures in °C)

Source	**Type**	**Mean**	**Max***	**Min**	**Abs Max**	**Abs Min**
Hobo+	In-situ logger	11.05	24.45	4.34	37.19	1.58
Met Station	Automatic weather station	10.20	14.97	5.44	19.00	2.50
CFSR	Reanalysis dataset (38 km²)	10.87	20.75	3.43	23.85	-0.15
ERA5 Ag	Reanalysis dataset (9.6 km²)	11.05	16.29	5.48	18.07	4.84
TerraClimate	Hybrid reanalysis dataset (4 km²)	12.21	18.34	6.08	20.30	5.10

+Max and Min are average monthly maximum and minimum temperatures, whereas Abs Max and Abs Min are the absolute minimum and maximum over the time period
**Hobo was for only 6 months- Sept-March.*

With regard to precipitation, the two datasets investigated were TerraClimate (which also has a precipitation component) and CHIRPS. CHIRPS (Climate Hazards Group InfraRed Precipitation with Station) is one of the more well-known precipitation datasets, particularly for use data-sparse areas such as Africa- where it has been used extensively for drought monitoring. It has a spatial resolution of 0.05 degrees and has been in operation from 1981 to present. It uses infrared Cold Cloud Duration (CCD) observations along with ground station data to provide a continuous and detailed precipitation dataset that covers the globe (Funk et al., 2015). The CHIRPS dataset has been compared with ground station precipitation data in Kenya and found to perform well under a variety of environments and for both seasonal and annual precipitation (Ayugi et al., 2019).

CHIRPS data was compared with TerraClimate data in the Teleki Valley by plotting a moving average for monthly precipitation across the whole time series. Overall, the TerraClimate data had larger peaks and valleys, but for the most part tracked fairly close with CHIRPS. The period around 2005-2006 is the period where there is biggest divergence between the two datasets.

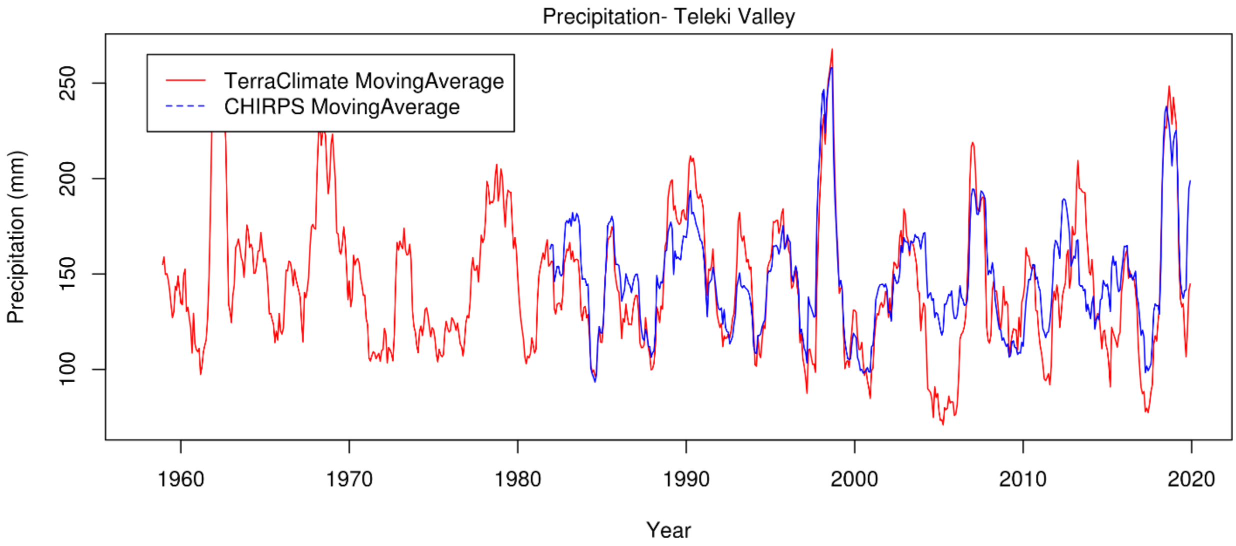

Figure A1-2 Comparison of TerraClimate and CHIRPS precipitation data in Teleki Valley

The current study used the TerraClimate dataset as the principal source of information on climate patterns on Mount Kenya and Mount Elgon. Whereas the temperature on average reads higher than the ground data, it has the longest temporal coverage and the finest spatial resolution. It is also a consistent dataset not having undergone any changes in the underlying algorithm. The finer spatial resolution also lends more confidence to areas further removed from Met Station, which is the only calibration station in the area. Similarly for precipitation patterns, the TerraClimate data appears to capture the precipitation extremes better than CHIRPS, and with a much longer time record.

A1.2 Meteorological Stations

The Centre for Training and Integrated Research in ASAL Development (CETRAD) was established in 2002, but it came out of the Laikipia Research Programme which had been operational since 1976. This programme focused on primarily on water resource issues in the arid regions of Laikipia surrounding Mount Kenya (CETRAD, 2022). CETRAD houses a fairly detailed network of weather stations, many of which have been operating since the 1960s. Several of the weather stations on the western slope of Mount Kenya were put in place by the Laikipia research station- through the Natural Resources Monitoring, Modeling and Management (NRM3) program (Notter et al., 2007). Other weather stations were put in place by the Kenya Forest Service at their guard posts. The Forest Service stations go back to the late 1950s but stop by 2007 and there are plenty of data gaps in between. They are arranged in a half circle around the lower slopes of the mountain at roughly 2000 m from the Ragati station in the southwest to Nanyuki in the northwest. The NRM3 stations go up the western slope of Mount Kenya starting at Munyaka (2070 m) all the way to the Teleki Valley station (4262 m). Most have fairly continuous data, although some were not operational for very long. CETRAD also has an extensive network of stream gauge stations on the western side of Mount Kenya, also put in as part of the NRM3 project. These gauges have been operating continuously since 1985 without many data gaps. These stations proceed down the western slope of the mountain following the Naro Moru and Burguret rivers (Notter et al., 2007).

The Kenya Water Resources Authority (WRA) maintains some 455 river gauging stations around the country in all the major drainage basins (http://www.wrma.or.ke/). Many of these gauging stations are no longer operational and others only have a short term observation record, but around Mount Kenya and Mount Elgon there a few that are still operational with a long-term record of discharge.

The current study used much of the CETRAD network of meteorological stations, but in particular the three that are actually on the mountain- Munyaka Station (2070 m), Gate Station (2420 m) and Met Station (3050 m). Of these Met Station is the closest to the alpine zone and so analysis focused on this station. Similarly for stream gauge stations, analysis focused on the highest elevation station- A3, which is below Met Station and whose catchment area includes the greater Teleki Valley.

A2 Vegetation analysis

A2.1 Mount Kenya vegetation surveys

There have been several attempts to characterize the vegetation on Mount Kenya. The Swedish researcher Olov Hedberg (Hedbeg, 1964) applied a generic scheme to all the afro-alpine mountains that he visited. His categories were based on the dominant vegetation which was in turn determined largely by valley position. These were: *Dendrosenecio* Woodlands, *Helichyrsum* scrub, *Alchemilla* scrub, Tussock grasslands, and *Carex* bogs (Table A-1). Later Malcom Coe (1967) used even simpler categories based purely on landform, in his study on the ecology of Mount Kenya (Table A-2). Later still in the mid-1980s, Rehder et al. (1988), tried to come up with more functional categories based on plant associations. They conducted a survey of the vegetation of Teleki Valley (Rehder et al., 1981) which they then applied to the whole alpine zone of the mountain to create the first vegetation map of the mountain top (Figure A-1; Rehder et al., 1988). The authors applied a similar scheme to Mount Elgon as well (Beck et al., 1987), altering the categories somewhat to account for the different physiognomic conditions. Their fieldwork, involving a series of quadrats placed in each plant type, gave them a tally of each species and enabled them to get a better idea of plant associations. (Table A-3). Other scientists-particularly Drs. T. Young, A. Smith, and E. Beck- were more interested in plant form and function, and conducting numerous experiments to better understand these unique plants. Many of these studies are compiled in the book 'Tropical Alpine Environments' edited by Rundel et al. (1994).

More recent studies have been mostly interested in biodiversity and genetic information in these ecosystems. Genetic analyses and inventory of afro-alpine species were conducted through the AfroAlp project (https://www.nhm.uio.no/english/research/projects/afroalp/), through Addis Ababa University and University of Oslo. Bbiodiversity surveys were undertaken by the were undertaken through the National Museums of Kenya in partnership with the Wuhan Botanical gardens (Zhou et al., 2017) and from this came a field guide in 2018 which is probably the most thorough field guide for the alpine zone yet.

The current study used the Rehder et al. (1988) classification scheme for differentiating vegetation types and focused on the 'Main Differentials' as the dominant species driving species assemblages. The Zhou et al. (2017) field guide was used as the primary reference along with a taxonomic key created by Young and Peacock (1985).

Table A2-1 Hedberg Plant Communities

Plant Community	Description	Major Species Mt Kenya	Major Species Mt Elgon
Dendrosenecio woodlands	Most unique and characteristic of the communities; can grow 4-6 m tall either as dense forest or open woodland; requires deep soil and good supply of water. Two main species in each mountain separated by elevation. Mt. Kenya*: S. keniensis* (below 4000 m) and *S. keniodendron* (above). Mt. Elgon: *S. elgonensis* (below 3900 m) and *S. barbatipes* (above). Undergrowth is *Alchemilla* spp, and tussock grasses.	*Senecio keniensis, Senecio keniodendron, Alchemilla gryophylla, Alchemilla johnstonii, Lobelia telekii, Heracleum elgonense; Cerastium octandrurn, Ranunculus oreophytus, Cardamine obliqua, Myosotis keniensis, Galium glaciale, Valeriana kilirnandscharica,Senecio keniophytum.*	*Senecio elgonensis, Senecio barbatipes, Alchemilla elgonensis. Alchemilla johnstonii, Cardamine obliqua, Sagina abyssinica, Peucedanum kerstenii, Marchantia polymorpha; Luzula johnstonii, Parietaria debilis, Arabis alpina, Anthriscus sylvestris, Heracleum elgonense, Myosotis vestergrenii, Senecio sotikensis; Euryops elgonensis, Lobelia telekii.*
Helichrysum scrub	Shrubs can grow up to 2 m in a variety of densities; common on rocky ground or porous sandy soil. Not as common in Elgon and Kenya as compared to elsewhere in the region. Main species for Mt. Kenya*: H. chionoides* (below 4000 m), and *H. citrispinum, H. brownei* (above). For Mt. Elgon: *H. citrispinum* and *H. amblyphyllum*.	*Helichrysum chionoides, Helichrysum citrispinum, Helichrysum brownei. Alchemilla argrophylla, Philippia keniensis, Blaeria filago, Senecio keniophytum, Nannoseris schimperi,*	*Helichrysum citrispinum and Helichrysum amblyphyllum, Helichrysum newii, Alchemilla johnstonii, Kniphofia snowdenii, Senecio snowdenii, Senecio elgonensis, Lobelia telekii, Carduus keniensis, and Peucedanum kerstenii.*
Alchemilla scrub	Less conspicuous shrubs but very prevalent. Found on gently sloping and well-drained soils. Common element of the other communities as well. Main species separated by edapthic conditions. Mt. Kenya: *A. johnstonii* (moist areas), *A. agryophylla* (drier ground). Mt. Elgon*: A. johnstonii* (moist areas), *A. elgonensis* (drier ground).	*Alchemilla agryophylla, Alchemilla johnstonii, Arabis alpina, Galium glaciale, Lobelia telekii, Myosotis keniensis, Oreophyton falcatum, Senecio keniodendron, Senecio purtschelleri.*	*Alchemilla johnstonii, Alchemilla elgonensis, Cardamine obliqua, Cerastium sp.,Galium spp., Oxalis corniculata, Senecio barbatipes, Valeriana kilimandscharica, Veronica glandulosa, Viola eminii.*
Tussock grassland	Most common type on the drier mountains; tall tussock-forming grasses- large and dense; fire adapted community. Most important community on Mt. Elgon and the western slope of the Mt. Kenya Dominant species is *Festuca pilgeri*	*Tussock Grasses: Festuca pilgeri, Poa spp. etc. Also present scattered shrubs/herbs: Alchemilla johnstonii, Senecio keniensis, Lobelia telekii, Senecio keniodendron, Senecio purtschelleri, Carduus platyphyllus,*	*Tussock Grasses: Festuca pilgeri, Agrostis gracilifolia, Andropogon amethystinus, Koeleria gracilis etc.*
Carex bogs (and related)	Found in areas of poor drainage with acidic peat soils; peat-forming communities of *Carex* and *Sphagna* mosses; generally occur lower in the alpine zone. Mt. Kenya dominant species is *C. monostachya* often with *L. keniensis/S. keniensis*; Mt. Elgon dominant species *is C. Runssoroensis*	*Carex monostachya, Lobelia keniensis, Senecio keniensis, Senecio keniodendron, Luzula abyssinica, Cerastium octandrum, Sagina afroalpina, Ranunculus oreophytus, Cardamine obliqua, Alchemilla johnstonii, Haplosciadium abyssinicum, and Myosotis keniensis.*	*Carex runssoroensis, Alchemilla johnstonii, Subularia monticola, Crassula granvikii, Limosella africana, Callitriche stagnalis Cardamine obliqua. Lobelia elgonensis and Lycopodium saururus.*

Table A2-2 Coe Plant Communities

TOPO FORM	Overstory	Understory	Other Plants
Valley Walls	*Senecio keniodendron* (upper)/*Senecio brassica* (lower)	*Alchemilla agrophylla (*sometimes *Agrostis trachyphylla)*	*Ranunculus oreophytus, Arabis alpina, Haplosiadium abyssinicum, Deschampsia flesuosa, Anthoxanthum nivale* in tussocks; between *Swertia kilimandscharica, Valeriana kilimandscharia, Galium rwenzoirense*
Valley Floors	Tussocks of *Agrostis trachyphylla, Festuca piligeri/abysinnica, Anthoxanthum nivale, Carex monostachya*	mosses*, Alchemilla johnstonii, Galium glaciele, Swertia volkensii, Romulea keniensis*	*Myostis kenienses, Nannoseris schimperi, Cerastium afromontanum, Cardus platyphyllus, Valeriana kilimandscharica*
Ridge Tops	*Alchemilla argyrophylla, Helichrysum cymosum, S. keniophytum, S. purtschelleri*		*Sedum rwenzoriense, Heracleum elogonense, Arabis alpina, Valeriana kilimandscharica*
Lakes and Tarns	*Subularia monticola, Crassula granvikii*	*Alchemilla johnstonii, Haplocarpha rueppellii, Rununculus oreophytus*	

Table A2-3 Rehder Plant Categories

Main Differentials	Accessory Differentials	Indifferent
Dendrosenecio battiscombei	*Asplenium aethiopicum*	*Lycopodium saururus*
Nidorella arborea	*Geranium arabicum*	*Swertia volkensii*
Protea kilimandscharica	*Kniphofia thomsonii*	*Helichrysum cymosum*
Hypericum keniense	*Cineraria grandiflora*	*Luzula abyssinica*
Stoebe kllimandscharica	*Galiolus watsonioides*	*Senecio purtschelleri*
Philippia keniensis	*Helichrysum chionoides*	*Dianthoseris schimperi*
Erica arborea	*Agrostis graclifolia*	*Cerastium afromontanum*
Alchemllia argyrophylla	*Vernoica glanulosa*	*Pentaschistis minor*
Festuca pilgeri	*Galium ruwenzoriense*	*Helichrysum forskahlii*
Carex monostachya	*Alchemilla johnstonii*	*Valeriana kilimandscharica*
Lobelia keniensis	*Swertia crassiuscula*	*Sagina afroalpina*
Dendrosenecio brassica	*Alchemilla cyclophylla*	*Blaeria filago*
Lobelia telekii	*Anthoxanthum nivale*	*Agrostis trachyphylla*
Dendrosenecio keniodendron	*Helicrysum brownei*	*Peucedanum friesiorum*
	Halpocarpha rueppellii	*Arabis alpina*
	Ranunculus oreophytus	*Subularia monticola*
	Festuca abyssinica	*Helichrysum citrispinum*
	Haplosciadium abbyssinicum	*Cardamine obliqua*
	Carduus chamaecephalus	*Agrostis spp.*
	Senecio keniophytum	

A2.2 Young & Peacock Survey

A unique historic study on vegetation communities in Teleki valley was conducted by Drs. Young and Peacock in 1980 (Young & Peacock, 1992). This study (field work from 1979/1980), attempted to survey vegetation across elevation and landform in the valley in order to understand the factors driving community composition in the alpine plant communities. The authors focused in particular on the *Dendrosenecio keniodendron* species, which they saw as being a critical species influencing community structure.

The survey by Young & Peacock (1992) incorporated 45 30 m transects (plots) located along 6 cross-valley transects. Each cross-valley transect was separated by 1 km, and within each, there were 7 sample transects (plots) based on valley position: north ridge, north slope, north valley bottom, riverside, south valley bottom, south slope, and south ridge. This made for 42 plots, to which a few more were added to account for additional topography at the head of the valley (see Appendix A). Each sample transect (plot) was 30 m long, running perpendicular to the slope. Ten (10) 1 m x 1 m quadrats were laid down at three meter intervals, and the presence of each vascular species was recorded. This then created a species presence score on a 1-10 scale for each plot. In addition all *Dendrosenecio* individuals (both *keniodendron* and *keniensis*) within 10 m of the plot centre-line were recorded. For the *D. keniodendron*, the height of each individual was recorded to the nearest half metre as well as the number of forks. In addition, environmental factors were recorded for each plot: slope, aspect, elevation, % rock, %bare ground/water, and % live vegetation. A topographic map obtained from the authors (Mary Peacock) had the transect locations marked by marker.

The Young & Peacock Survey was unique in that it was both an in inventory of plant communities as well as a study on factors driving plant community distribution. The 45 sample transects were arranged to capture the elevation, slope, and aspect variations across the entire Teleki Valley (Figure A1-2). Since the valley is oriented E-W, and is located on the equator, the whole valley gets somewhat uniform exposure to sunlight- but nonetheless there are slight seasonal variations and daily variability in terms of when different parts of the valley receive sunlight each day. The shape of the valley is fairly consistent deep V-shape for the majority of the valley, but the upper end brings in some different topography as the Naro Moro river forks with one fork leading to the Teleki Tarn and the other from the Hut and Tyndal Tarns.

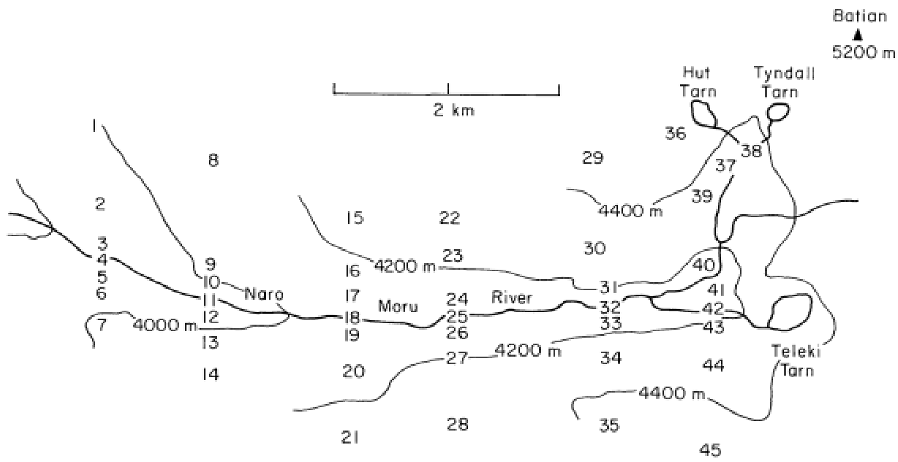

Fig. 1. The locations of the 45 transects in the upper Teleki Valley on Mount Kenya.

Figure A2-1 Sampled transects in the Teleki Valley in 1980- Young and Peacock, 1992

Generally the authors found that the vegetation consistently by elevation and slope position, with only minor differences according to aspect. They assigned a Rehder plant type to each transect and found most of their types present in the valley although the O and K types predominated. These are the *Dendrosenecio keniensis (brassica*)/ *Lobeila keniensis* type and the *Dendrosenecio keniodendron/Lobelia teleki* type. They were not able to always assign a single 'type' to each transect, showing the somewhat subjective nature of these types.

For the current study, the procedures of Young and Peacock (1992) were followed as closely as possible, with some modifications. The original transects were placed before the days of GPS and so they were not equally spaced. Using GIS to place the transects at 1km intervals put the last transect last transect further up the valley than in the original study. This put it in mostly rock terrain with very little vegetation, and outside of the main confines the Teleki Valley. Even the original transect crossed the two forks of the Naro Moru river, which somewhat confounded the valley positions. The authors added in additional plots to account for the extra terrain. Rather than attempt such modifications, the last cross-valley transect was simply dropped from this study leaving just 35 plots: 5 cross-valley transects x 7 sample transects (plots). The rest of the procedures were followed exactly as described in Young & Peacock (1992), except for the ground cover classifications were simplified to % live vegetation and % other, since even in the original field notes there was sometimes confusion over what was rock, and what was bare ground or detritus.

The analysis in the Young and Peacock (1992) study focused mostly on descriptive statistics to describe vegetation patterns in the valley. The relationship between species and environmental variables were compared using a Canonical Correspondence Analysis ordination (ter Braak, 1987). In 1980, and the most significant environmental factors came out to be % vegetation cover (by inference moisture), altitude (by inference temperature), and mean *D. keniodendron* height (by inference plant facilitation effects). The same CCA was run again for both 1980 and 2021 but using only the 35 repeat transects and also a running a Non-metric Multidimensional Scaling analysis on the combined dataset to show shifts from 1980 to 2021 according to these environmental factors.

For comparisons between 1980 and 2021, the non-parametric Wilcoxon signed rank test was mostly used. This is a paired difference test (analogous to the Student's T-test), as each site in 1980 and 2021 was considered as a pair, since theoretically they were the same area. The choice of non-parametric tests was because for the most part the species data did not conform to the requirements of parametric tests, namely; constant variance and normal distribution. These factors were tested with the Shapiro-Wilk normality test and the F-test for variance. With regard to diversity, the Simpson's index was used rather than the more common Shannon's index. Simpson's is more of a dominance index, giving more weight to dominant species. Given that grasses were excluded from this dataset, and there was uncertainty over some of the less common species, it was felt that Simpson's was the more appropriate measure to assess diversity. Simpson's index is useful where there is a dominant cover type since a few uncommon species will not affect overall diversity that much (Nagendra, 2002).

A2.3 Landscape Patterns Analysis

Landscape vegetation patterns can be quantified to understand underlying plant-plant interactions. Berdugo et al. (2017) carried out an assessment of vegetation patterns to ascertain the relationship between patch size distribution and different biotic and abiotic factors. The authors used a combination of high resolution satellite images with at least 30 cm spatial resolution, and segmented the images using a luminance threshold. They then classified each image using a k-mean classification approach. The authors classified imagery for 127 desert sites across the globe. For each site, three 50m x 50m squares were extracted and pooled to get an overall patch distribution for each site. A power-law was then fitted to the distribution and a Power Law Relative Range (PLR) was calculated as:

$$\mathrm{PLR} = 1 - \frac{\log_{10}[x_{\mathrm{min}}] - \log_{10}[x_{\mathrm{smallest}}]}{\log_{10}[x_{\mathrm{max}}] - \log_{10}[x_{\mathrm{smallest}}]}$$

where X_{min} is minimum patch size from which the fit to a power law starts, $X_{smallest}$ is the size of the smallest patch and X_{max} is the size of the largest patch in the image. This varies from 0 to 1 and a cut off of 0.57 to divide the “PowerLaw Like” (PL-like) and “PowerLaw unLike” (PL-unlike) sites. The study found that patch size distribution either fit a power-law curve or did not, and that the PL-like areas were dominated by plant facilitation, whereas the PL-unlike areas were dominated by abiotic gradients.

The current study used a similar classification approach to that of Berdugo et al. (2017). Plaeiades imagery (50 cm resolution) was segmented according to luminance and Normalized Difference Vegetation Index (NDVI). The first band of a Principal Components Analysis (PCA) image (which generally corresponds to albedo effects), was segmented by the threshold of 750. This seemed to best separate the woody vegetation patches from the surrounding environment, though it also included non-vegetative extrusions such as large rocks. A NDVI threshold of 0.45 appeared to best differentiate the rocks from the woody vegetation. This was then re-sampled to 2 meter resolution (to remove some the random noise) and converted to polygon. A 1ha by 1ha square was extracted at each of the 35 valley transect locations. This larger size was in order to get a reliable estimate of distribution, instead of pooling three 50 mx 50 m squares. A power-law was fit to each square for frequency of patches by patch size. Sites with clustered patches follow a power-law distribution, whereas those with a more even distribution of patches and sizes do not.

The power-law it was fit using the R package plfit: (http://tuvalu.santafe.edu/~aaronc/powerlaws/). This can be applied to any list of patches, sorted by size. The parameters of the function are *Xmin* and *Alpha*. *Xmin* specifies the minimum patch size from which a power law fit starts, and Alpha is the slope of the Power Law function i.e. “the rate of decline in the number of patches with their size” (Berdugo et al., 2007).

To demonstrate the Power-Law relationships see the example below from the Teleki Valley. Test Area1 has much more large vegetation patches that are clustered together, whereas Test Area 2 has small, scattered patches (Figure A3-1). Test Area1 more or less fits a Power Law (PLR of 0.53) whereas Test Area 2 does not (PLR of 0.31).

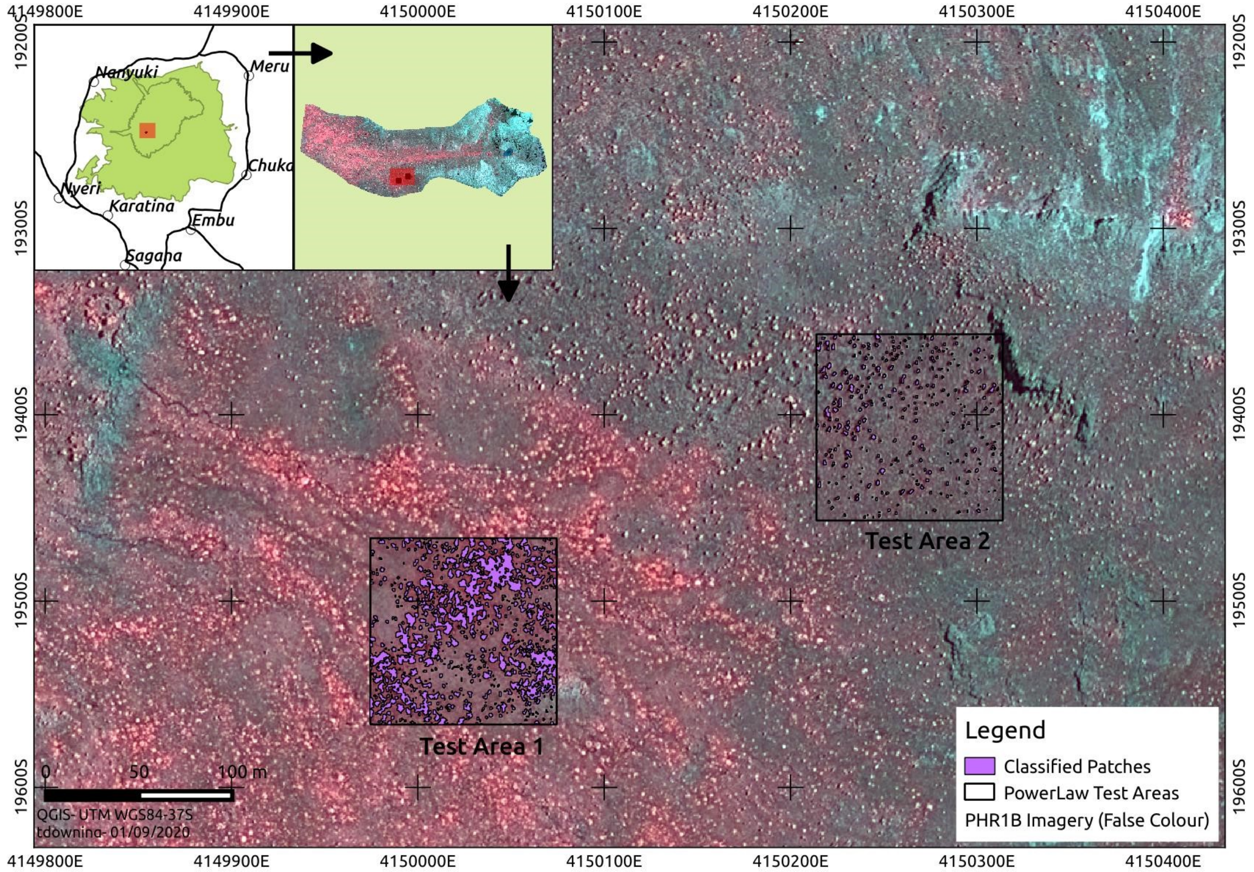

Figure A2-2 Sample areas in Teleki Valley with classified patches

A3 Socio-economic Analysis

A3.1 Questionnaires

Sampling for the household questionnaires was done by means of a cluster strategy. This was to allow for more efficiently covering the study area. The sample size calculated, using the traditional formula, came to 138. It is recommended to increase the sample size by 50% when utilizing a cluster approach, so a total sample size of 207 was used. 25 clusters were chosen to allow for roughly 10 samples per cluster (Table A4-1).

The administrative sub-location was then used at the basis for the clusters. A list of all the sub-locations in the study area was obtained. These were all the sub-locations that fell within 20km of the alpine zone within Bungoma and Nyeri counties. The total number of households within this area came to 79,235. Dividing this by the 25 clusters brought a sample interval of 3169. The sub-locations were then all arranged in a list and a cumulative tally of household population was included in a separate field. Starting from a random start point (2144), clusters were chosen by counting off by 3169 increments and choosing the sub-location whose cumulative population tally fell into that interval (Table A4-2).

Questionnaires were administered in March and April, 2021. Each sub-location was visited sequentially and the questionnaires were administered to willing participants until the sample size had been reached. Then the next closest sub-location was visited. Questionnaires were administered by the author and his field assistant, sometimes with the help of a local informant.

Table A3-1 Clusters chosen (with probability proportional to size) for administering questionnaires

SUB-COUNTY	LOCATION	SUB-LOCATION	*Modification	Total Pop	Households	Sample Target	Sample Actual
CHEPTAIS	CHEPKUBE	CHEPKUBE	Chepkube + Chebwek	8303	1722	11	11
CHEPTAIS	CHEPTAIS	NGACHI		12365	2812	18	18
CHEPTAIS	CHESIKAKI	CHEMONDI		7137	1352	9	9
CHEPTAIS	CHESIKAKI	TOROSO		4697	962	6	6
CHEPTAIS	CHONGEYWO	KAPKURONGO		3771	735	5	6
CHEPTAIS	CHEPYUK	KAIMUGUL		9179	1480	9	10
CHEPTAIS	EMIA	EMIA	Chepyuk	4783	932	6	5
CHEPTAIS	KAPKATENY	CHEPTONON		4560	907	6	6
MOUNT ELGON	ELGON	KIBUK		3832	779	5	5
MOUNT ELGON	KAPSOKWONY	CHEMWEISUS		4840	957	6	5
MOUNT ELGON	NOMORIO	SAMBOCHO		2866	521	3	3
MOUNT ELGON	KABOYWO	KABOYWO		5452	985	6	6
MOUNT ELGON	KONGIT	KAPTALELIO	Kongit	4306	794	5	6
KIENI EAST	CHAKA	CHAKA	Mbiriri	4277	1694	11	11
KIENI EAST	KABARU	KAIRI		3349	1083	7	8
KIENI EAST	KABARU	NDATHI		2382	696	4	6

KIENI EAST	THIGU	THIRIGITU		3804	1201	8	8
KIENI EAST	WARAZO	MUNYU		2644	872	6	6
KIENI EAST	GAKAWA	EQUATOR	Kaaga	8575	3082	20	16
KIENI EAST	GAKAWA	KAHURURA		6487	2295	15	15
KIENI EAST	GITHIMA	GATHIURU		3196	1147	7	10
KIENI EAST	KAMBURAINI	KAMBURAINI		2921	879	11	11
KIENI EAST	KIAMATHAGA	GIKAMBA		4138	1256	8	8
KIENI EAST	KIAMATHAGA	TIGITHI	Njoguini	2453	773	5	5
KIENI EAST	NAROMORU	NDIRITI		4469	1357	9	9
TOTAL						**206**	**209**

** Modifications: Some clusters were switched to a different sub-location for logistical reasons- either the selected sub-location was too far from the forest, or there was problems accessing the selected sub-location.*

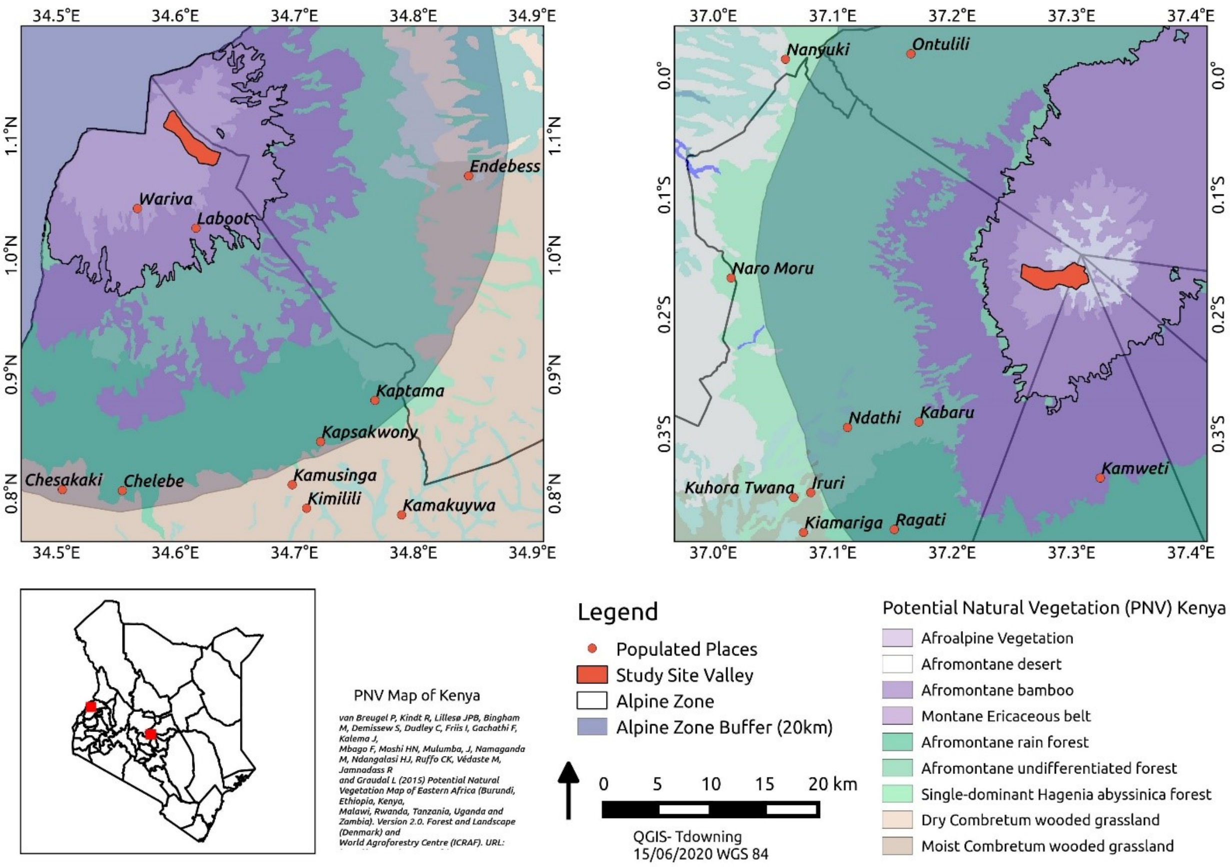

Figure A3-1 Potential Natural Vegetation Map for the two study areas with the closest populated places to the study area valleys. These were the places targeted for the questionnaires

A3.2 Questionnaire Tool

NAME OF INTERVIEWER ________________VILLAGE/ AREA _____________________________

DATE (D/M/Y): _______________________________

START TIME: _______________________________END TIME: _____________________________________

The purpose of this questionnaire is to **gain an understanding of the interaction with local communities and alpine environments. The questionnaire seeks to explore what ecosystem services communities derive from alpine areas and what changes they have observed over the years.** This questionnaire is part of an independent study being conducted by **Timothy Downing**, a PhD student from The University of Nairobi. Any information you provide **will** be used anonymously. You do not have to answer any question you do not feel comfortable with and you can stop the interview process at any time. You can ask for clarification on any question at any time. We would be very grateful if you could participate. Thank you for your cooperation

A. General Information

Name: _______________________ **Age**: ________________________ **Ethnicity**:_______________________

Gender: Male ☐ Female ☐

Highest Education Level: Primary School ☐ Secondary School Diploma University Degree Post-graduate Degree

Do you live here most of the time? Yes ☐ No

Did you move to this area? Yes ☐ No

What is your main occupation?

Labourer ☐ Farmer ☐ Business☐ Government ☐ Professional ☐

Others (Specify) _______

The following questions deal with mountain resources. First we will ask some questions about your level of knowledge regarding this area and then your attitudes and perceptions regarding the natural resources found in this area.

B. Alpine Resources

How frequently do you visit the alpine zone of the mountain?

Very Frequently ☐ Frequently ☐ Somewhat Frequently Rarely ☐ Never

How important is the alpine zone of in your every day life?

Very Important ☐ Important ☐ Somewhat Important ☐ Minimally Important Not important

How would you rank your own level of knowledge about the alpine zone- it's history and resources?

Very High ☐ High ☐ Moderate Low ☐ None ☐

If alpine zone was gone what do you think impact would be?

Very Large impact ☐ Large impact ☐ Moderate impact ☐ Minimal impact ☐ No impact ☐

What do you see as the main benefits of the alpine zone?

Benefits	Tick where appropriate
Livestock Forage	
Food Gathering	
Agriculture	
Medicine	
Water	
Recreation	
Ceremonies	
None	
Other____	

Were there benefits derived from the alpine zone in the past that are no longer used?
Specify_____________________________

What changes have you noticed in the alpine zone in your lifetime?

Changes	Tick where appropriate
Temperature	
Species range	
Species composition	
Streamflow	
Water quality	
Soil Fertility	
Rainfall pattern	
None	
Other____	

C. Climate Change

Have you experienced persistent changes in climate in your community? Yes ☐ No ☐

What climate changes have you observed?

Drought ☐ Flooding ☐ Temperature increases ☐ Declining yields ☐ Increased disease ☐ Erratic Rainfall ☐ Other/None ________________________

Which strategies have you used to deal with these changes?

Move ☐
Change food source ☐
Change agricultural practices ☐
Diversification of income sources ☐
Change water supply ☐
Appeal to government/NGOs ☐
None ☐
Any other specify_____________________________

What is the biggest challenge facing Kenya today

Climate Change ☐ Employment ☐ Healthcare ☐ Safety/Security ☐ Education ☐

Food/Water Availability☐ Other ____________________________

The questions below will ask you to rank our opinion on each subject on a scale from 1 to 5: 1= Very High, 5=Very Low. If you have no opinion you can just pick the middle value- neutral.

D. Ecosystem Services (benefits) derived from the alpine/mountain resources

Rank the following Ecosystem Services coming from the alpine zone in terms of importance and, and then rank how much they have changed over your lifetime.

Ecosystem Service/Benefits to people	**Core Ecosystem Service**	**Rank the Core ES selected** ***(1= most important;5= least important)***	**Rank the change in ES over your lifetime** ***(1=most change; 5= least change)***
Provisioning	Food production		
	Raw material supply		
	Water supply		
	Medicines		
	Livestock forage		
Cultural	Cultural heritage/Spiritual value		
	Recreation		
	Tourism		
	Education		
Regulating/ Supporting	Climate regulation		
	Habitat for wildlife		
	Water purification		
	Nutrient cycling		

E. Attitudes and perceptions of the values of alpine resources and climate change

The following are statements regarding <u>utility and availability</u> of ecosystem services derived from the alpine resources. *Mark if you strongly agree [5], agree [4], neutral [3], disagree [2], strongly disagree [1] with the statements.*

- The alpine zone and its resources are important in my everyday life
- Alpine zone resources are free and available to all
- The alpine zone has additional value beyond what my community gains from it

The following are statements regarding the <u>interaction of climate</u> and alpine environments. *Mark if you strongly agree [5], agree [4], neutral [3], disagree [2], strongly disagree [1] with the statements.*

- The alpine zone is vulnerable to climate change
- Services provided by the alpine zone has declined in availability over the years
- I fear that alpine resources may be lost forever if climate changes continue

The following are statements regarding <u>capacity for adaptation</u> to climate change with respect to alpine resources. *Mark if you strongly agree [5], agree [4], neutral [3], disagree [2], strongly disagree [1] with the statements.*

- If alpine resources are lost forever it will have no impact on me or my community
- My community has the ability to handle future climate change impacts on alpine resources
- I have the support I need to deal with potential future loss of alpine resources

A3.3 Focus Group Discussions and Interviews

Focus group discussions were conducted at each study area with stakeholder groups (Table A4-3). In Mount Elgon, one group comprised of the Cheptais Community Forest Association which was an existing organization with its own structure and leadership. The other group was a collection of youths in Laboot who were gathered randomly to provide their views. The first group engaged in various forestry projects in the area and had an important perspective on forest resources, whereas the second group were livestock herders in the upper alpine zone and so had a unique perspective on alpine resources. For Mount Kenya also there were two groups: the first was a Water Resource Users Association, which again was an organized structure and had important perspective on water resource. The second group was a group of guides who were gathered randomly to provide their experience with changes seen during their guiding trips.

Table A3-2 Focus Group Discussion Details

Organization	**Location/ Study area**	**Primary Contact**	**Focus Group Members**	**Moderator/Note-Take**	**Date/Time**
N/A- selection of youth in the Ogiek community	Laboot/ Mount Elgon	N/A	Patrick, age 54 Isaac, age 32 William, age 49 Joel, age 21 Eric, age 23 Felix, age 30	Moderator = Dennis Nabie Note-taker = Timothy Downing	March 10th, 2021: 10:00am (42 minutes)
Cheptais Community Forest Association (CFA)	Chongwe/ Mount Elgon	CFA Chairman Joseph Kiptek	Noah Nabie, age 53 Ben Masombo, age 61 Francis Kasuswa. age 59 Jotham Chongeywa, age 82 Joseph Kiptek, age 63 Edward Masenge, age 60	Moderator = Dennis Nabie Note-taker = Timothy Downing	March 16th, 2021: 11:00am (80 minutes)
Mount Kenya Guides and Porters Club	Naro Moru/ Mount Kenya	Samson Kihara- Guide	Samson Kihara, age 32 David Wanjohi, age 41 John Keguta, age 34 Elijah Mbiti, age 38 Hans Mwangi, age 22	Moderator = Timothy Downing	April 10, 2021- 10:30am (65 minutes)
Naro Moru Water Resources Users Association (WRUA)	Naro Moru/ Mount Kenya	WRUA Secretary Justin Munene	Ephraim Kahenyi, age 50 Margaret Njege, age 56 Daniel Kamau, age 72 Esau Kibiru, age 61 Justin Munene, age 26	Moderator = Timothy Downing Note-taker = Dennis Nabie	April 20, 2021: 9:30am (65 minutes)

For interviews, five people were selected who were known to have extensive experience and knowledge in natural resource management. This included two retired chiefs, a senior guide, a council elder, and a chairman of a CFA (Table A4-4). Each of these interviewees provided valuable information on ecosystem services and changes that they had seen within their lifetimes.

Table A3-3 Key Informant Interviews

Name	Position	Location/ Study Area	Date
Johnson Cheprot	Chairman of the Ogiek Council of Elders of Chepkitale Reserve	Chebyuk/ Mount Elgon	March 21, 2021- 2:30pm
Ruben Rure	Retired Chief of Namwela Location	Namwela/ Mount Elgon	March 29, 2021- 11:00am
James Kagambi	Senior Mountain Instructor for Mount Kenya	Naro Moru/ Mount Kenya	April 10, 2021- 12:30pm
Moses Githeria	Chairman of the Gathiuro Community Forest Association (CFA)	Burguret/ Mount Kenya	April 13, 2021- 10:00am
Paul Gathogo	Retired Senior Chief of Naro Moru Location	Blue Line/ Mount Kenya	April 20, 2021- 12:30pm

The analysis approach can be thought of as a mixture of between a Grounded Theory approach and a Phenomenology (Creswell, 2013). The transcripts were explored in depth using open coding to extract themes and then axial coding to explore relationships between codes, with the goal of unearthing overarching theories as to how respondents interact with mountain resources. However there was also an element of Phenomenology to the study, as it was also an attempt to understand the shared experience of climate change among residents of the mountain regions of Kenya. To this end, ‘thick’ descriptions of climate change and ecosystem services were extracted to capture the essence of this experience (Creswell, 2013).

A3.4 Interview/Focus Group Question Guide

(Introduction)
My name is Timothy Downing- PhD student at the University of Nairobi, studying impact of climate change on the alpine areas of Kenya. I am interested in hearing your views on the matter. As you have lived on the Mountain and know it better than anyone, we wanted to know what types of changes you have experienced and how that has impacted the services that you get from the mountain, and what types of solutions you would propose.

(Overview)
- Can you tell us a bit about yourself? Who are you, what is your connection to the mountain? What is your work?

(Ecosystem Services)
- How important is the mountain in your everyday lives? What services does the mountain provide?
- Does the community utilize the alpine/moorland zone now or in the past? What do you see as the principal value of the moorlands? What specifically is it used for?
  - Nutritional/medicinal plants?
  - Cultural traditions?
  - Raw materials?

(Climate Change)
- What changes have you noticed in the mountain, and specifically the moorland zone, over your lifetime?
  - Vegetation changes- shifts in range or species?
  - Changes in wildlife movements?
  - Changes in temperature or rainfall patterns (seasonal or daily)?
  - Changes in water or soils coming off the mountain?
- What do you attribute these changes to?
- What ecosystem services do you think will most be affected by these changes?
- Do you anticipate these changes will continue? How do you think they will affect your day-to-day life?

(Adaptive capacity)
- What activities have you been involved with to cope with changes in the environment?
- What solutions do you propose if climate continues to change and impact the services the mountain provides?
- What questions are of interest to you regarding climate change in alpine areas? What do you think needs to be studied more?
- How has climate changes been dealt with in the past?
- What myths and legends exist concerning the mountains?
- How important is the sense of place in these myths/legends- are there landscape patterns that have importance for the community?

APPENDIX B: Plates

B1 Hobo Pendant Locations on Mount Kenya and Mount Elgon

Plate B1-1: 3000 m (Mount Kenya Met Station)

Plate B1-2: 3200 m

 (Mount Kenya)	 (Mount Elgon- Hobo could not be relocated in February, 2022)

Plate B1-3: 3400 m

 (Mount Kenya)	 (Mount Elgon)

Plate B1-4: 3600 m

 (Mount Kenya)	 (Mount Elgon)

Plate B1-5: 3800 m

(Mount Kenya)

(Mount Elgon)

Plate B1-6: 4000 m

 (Mount Kenya)	 (Mount Elgon)

Plate B1-7: 4200m

(Mount Kenya)

(Mount Elgon- 4100m)

B2 Comparison of current photographs with historic photographs

Plate B2-1: Upper Teleki Valley with view of the peak

Fig. 103. Kenya, Mt Kenya, Head of Teleki Valley, with the twin peaks in the background. The narrow pillars on the valley bottom in the foreground are inflorescences of *Lobelia keniensis* (cf. p. 60). Photo Å. Holm July 1948. The thermograms in Fig. 8 were recorded on the other side of the valley, at the little promontory extending into the valley bottom at the middle of the photo.

Hedberg, 1964 (Photo from 1948) ~4100m

Plate 7. Interdigitating stands of *Senecio keniodendron* (dark) and *Senecio brassica* (light), on the wall of the Teleki Valley: 13,800 feet.

Coe, 1967 – 4206m

Sept 28, 2021 ~4100m

Sept 28, 2021- 4206m

Plate B2-2: Teleki Valley bottom (facing West)

Plate 9. Glacio-fluvial flats at the head of the Teleki Valley: 14,000 feet. Note the moraine on the right, and the large areas of bare ground due largely to frost soil phenomena.

Coe, 1967- 4267m

Sept 29, 2021- 4116m

Plate B2-3: Old growth Dendesenecio keniodendron *stand- Teleki Valley*

Fig. 83. View of the *Senecio keniodendron* woodland described bel●w. The dominant plant of the tree layer is *Senecio keniodendron*, of the field layer *Alchemilla argyrophylla* ssp. *argyrophylla*. Note the wilted old inflorescences hanging down from the Senecios in the foreground. Kenya, Mt Kenya, Teleki Valley, 4100 m. Photo O. Hedberg 2.8.1948. Cf. also Figs. 33 and 84.

Hedberg, 1964 (Photo 1948) ~4100m

Sept 27, 2021 ~4000m

Plate B2-4: Large Dendesenecio keniodendron *individual with person for size comparison- Teleki Valley*

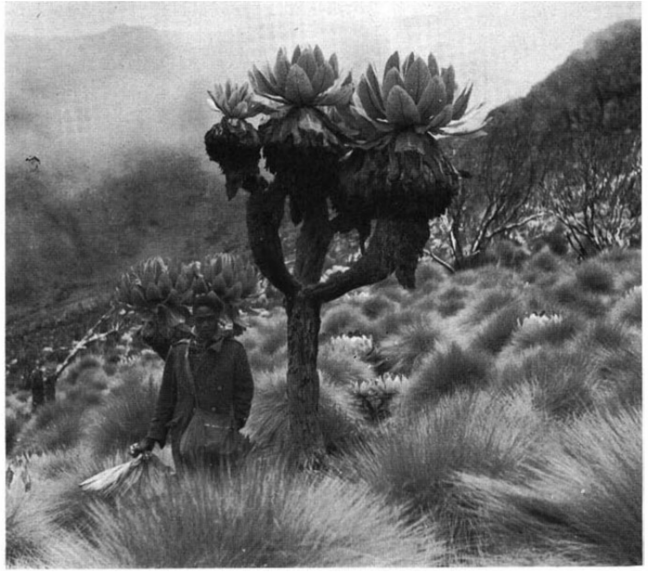

Fig. 22. Specimen of *Senecio keniodendron* damaged by fire, which had burnt off its cylinders of dry leaves around the stems. According to Mr. V. Klarville, Naromoru, this part of the valley had been burnt in 1943, so it had taken 5 years for the Giant Senecio to form the 4–5 dm long cylinders of dry leaves shown in this figure. The *Philippia* shrubs in the background to the right had been killed by the fire, whereas the grass (mainly *Festuca pilgeri* ssp. *pilgeri*) showed luxuriant growth. Kenya, Mt Kenya, on the ridge S of Teleki Valley (along the Naro Moru route), 3900 m. Photo O. Hedberg 12.8.1948.

Hedberg, 1964 (Photo 1948) ~3900m

Sept 27, 2021
~4000m

Plate B2-5: Dendesenecio keniensis *moorland community- Teleki Valley*

Photo 6. ***Dendrosenecio brassica*-Moorland-Community (I) on the Naro Moru Track at 3900 m altitude. The photo was taken (by E. BECK) in October 1980 when the majority of the cabbage groundsels had been or were still flowering.**

Rehder et al., 1981 ~3900m

Feb 22, 2022 -3647m

B3 Dendrosenecio Photographs

Plate B3-1: Dendrosenecios *of Mount Kenya and Mount Elgon*

	
D. elgonensis- Koitobos Valley- 3875m	*D. keniensis*- Teleki Valley- 3929m

D. barbatipes- Koitobos Valley- 4057m

D. keniodendron- Teleki Valley- 4067m

Plate B3-2: Flowering Dendrosenecios- Teleki Valley

Flowering *D. keniensis*- Sept 21, 2021	Flowering *D. keniodendron*- Feb 22, 2022
	

APPENDIX C: Supplementary Results

C1 Climate

C1.1 Discharge trends- baseflow

There is no meaningful trend in baseflow for any of the WRA stations surrounding Mount Kenya or Mount Elgon. While the trend for certain stations is significant according to the Mann-kendall test (Koitobos, Malakisi, Muhuhi, Lower Sagana), the slope of the trend is very slight, and the lowess line generally is a fairly flat line or else curved- suggesting no consistent trend. And for all of these time series there is a discrepancy between ADF and KPSS on whether the trend is stationary or not. While the two tests can sometimes legitimately provide different results, it also can suggest that there is confusion as to the stationarity of the time series (Sjosten, 2022)

The Mount Elgon stations have a much higher baseflow than the Mount Kenya stations. All six stations are located at similar elevations (~ 2000m a.s.l.) and all are located roughly 20 km from the alpine zone. The Malakasi station south of Mount Elgon had much baseflow than the other Mount Elgon stations. This station is located closest to the windward side of the mountain (generally the SE side). All the Mount Elgon stations had higher baseflow than the Mount Kenya stations; this is due to these stations being closer to the windward side of the mountain, but also may reflect different landcover conditions in the contributing catchments as well as stream water abstractions.

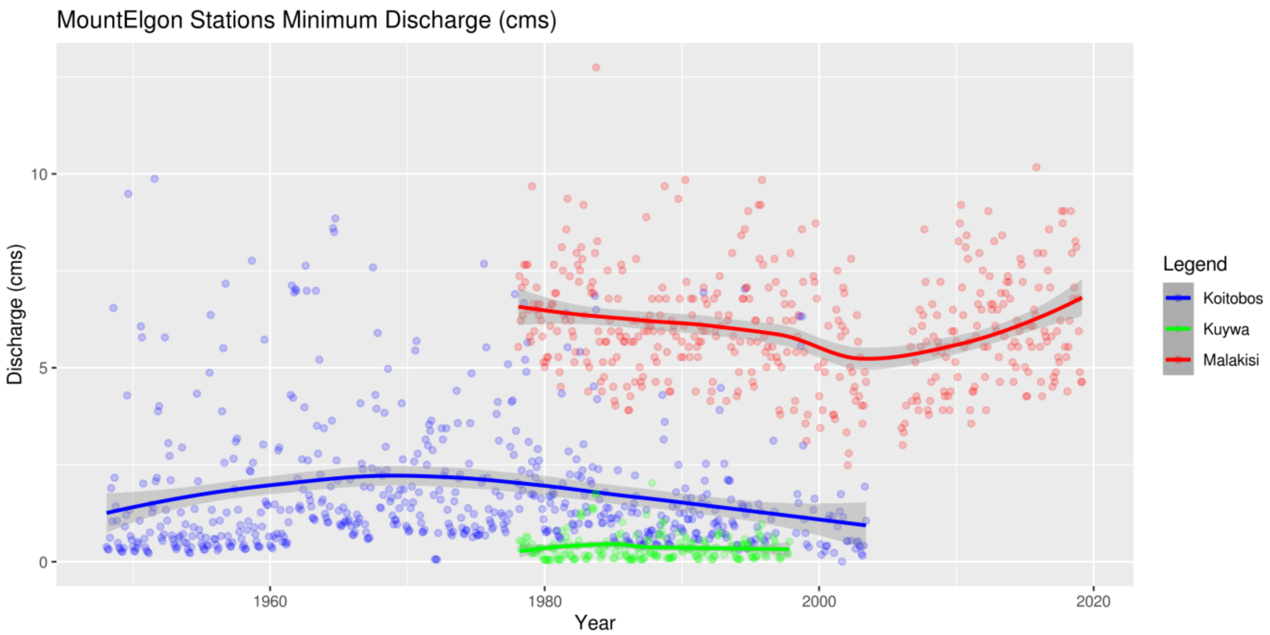

Figure C1-1 Minimum discharge trends for three gauge stations at the base of Mount Elgon

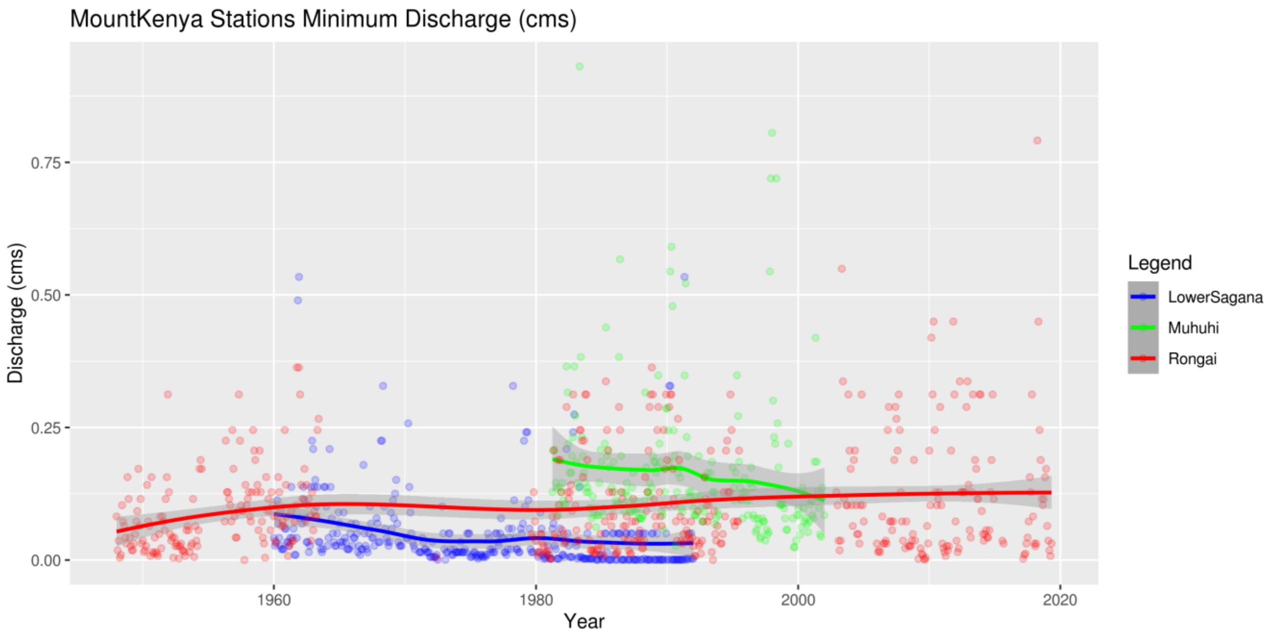

Figure C1-2 Minimum discharge trends for three gauge stations at the base of Mount Kenya

The NRM3 stations on Mount Kenya are located on the western side of the mountain. In these stations, baseflow is very low- less than 1 cms, and frequently reaching zero. A3, A5, and A6 are located along the Naro Moru river in order of stream position. It is interesting that the A6 gauge, which is furthest downstream- and thus has the largest catchment area- has the lowest baseflow. This is apparently due to water abstractions that occur from the foot of the mountain down to the confluence with the Ewaso Ngiro river, where the A6 guage is located (Notter, 2003; Liniger, 2005).

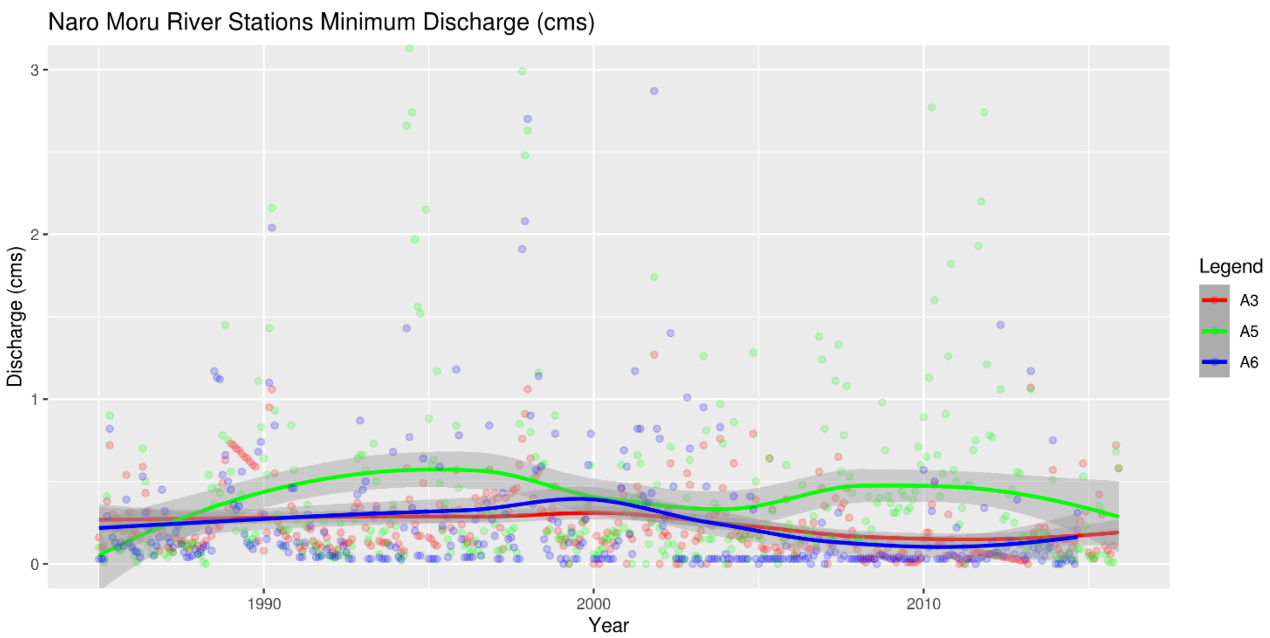

Figure C1-3 Minimum discharge trends for the three gauge stations along the Naro Moru River

C1.2 Precipitation trends below Mount Kenya

For the forest service stations surrounding Mount Kenya, monthly precipitation is almost the same for all the stations with the exception of Ragati- the furthest station to the south, which has noticeably higher precipitation. Ragati is on the south-east side of the mountain, which is closer to the windward side. There is no obvious trend in precipitation, but it does appear according to the lowess line that several stations have a slight negative slope. Indeed, this trend is significant for Naro Moru, Naro Moru FG, and the Kabaru stations according to the Mann-Kendall test.

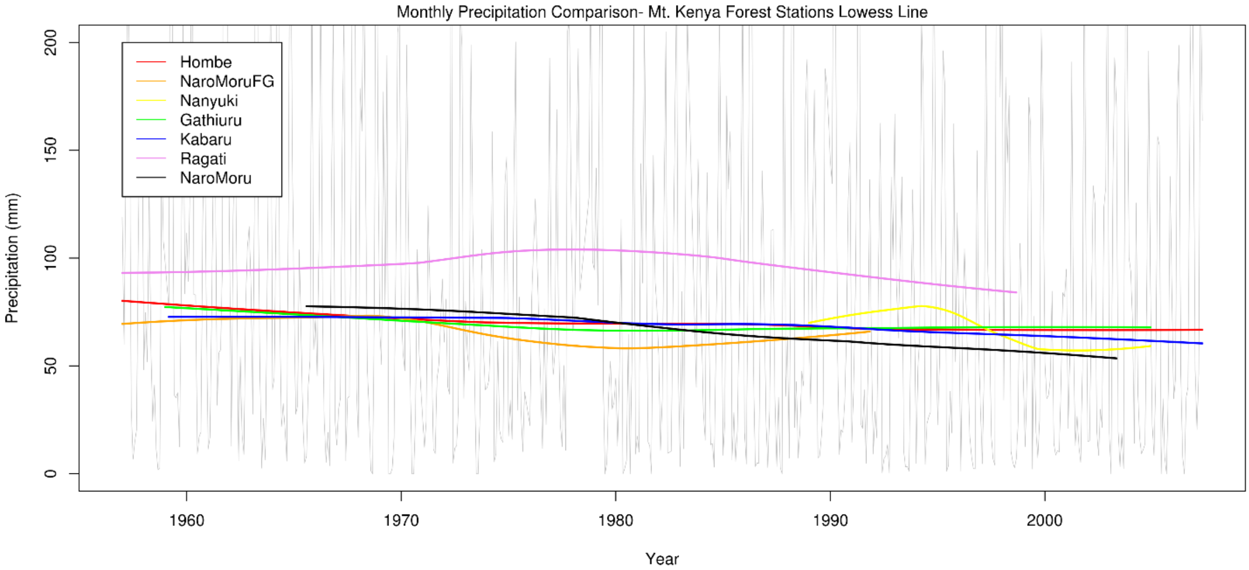

Figure C1-4 Monthly precipitation trends for the Forest Service weather stations at the western base of Mount Kenya

Despite the similar total precipitation amounts, the Forest Service weather stations display differences in seasonal precipitation. The station furthest to the north is Nanyuki with rainy seasons prominently in April and November. Naro Mour which is due west of the mountain has a similar pattern but with a more pronounced short rainy season in November and December. Finally Ragai, which is located furthest to the south- and with a greater total precipitation- has more pronounced rainy seasons in April/May and November/December.

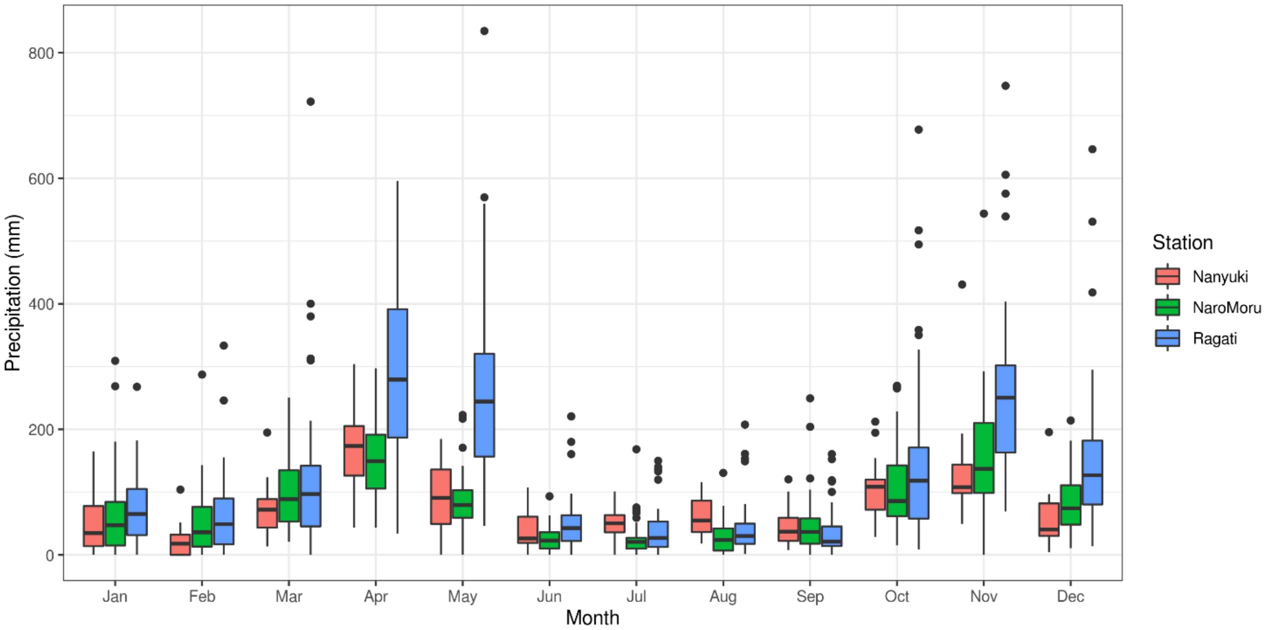

Figure C1-5 Seasonal precipitation patterns for three Forest Service weather stations at the western base of Mount Kenya

C1.3 TerraClimate Trends

The TerraClimate temperature data shows a consistent linear trend for mean temperatures. The same is true for maximum and minimum temperatures. When compared with historic observations over the course of the time series, it seems that TerraClimate does not capture the full range of variability, with maximum temperatures lower than reported values and minimum temperatures higher. These could be a function of instrumentation errors in the historic observations (which is likely the case for the Grab et al. (2004) temperatures (values from 1990).

Table C1-1 TerraClimate trends in Koitobos and Teleki valleys for minimum and maximum temperatures

Valley	**Satellite**	**Type**	**Mann-Kendall Test (2-sided) (Null= No Monotonic Trend)**
Koitobos	TerraClimate (1958-2020)	Maximum	**8.60 (p<0.01)**
		Minimum	**14.77 (p<0.01)**
Teleki	TerraClimate (1958-2020)	Maximum	**6.68 (p<0.01)**
		Minimum	**10.65 (p<0.01)**

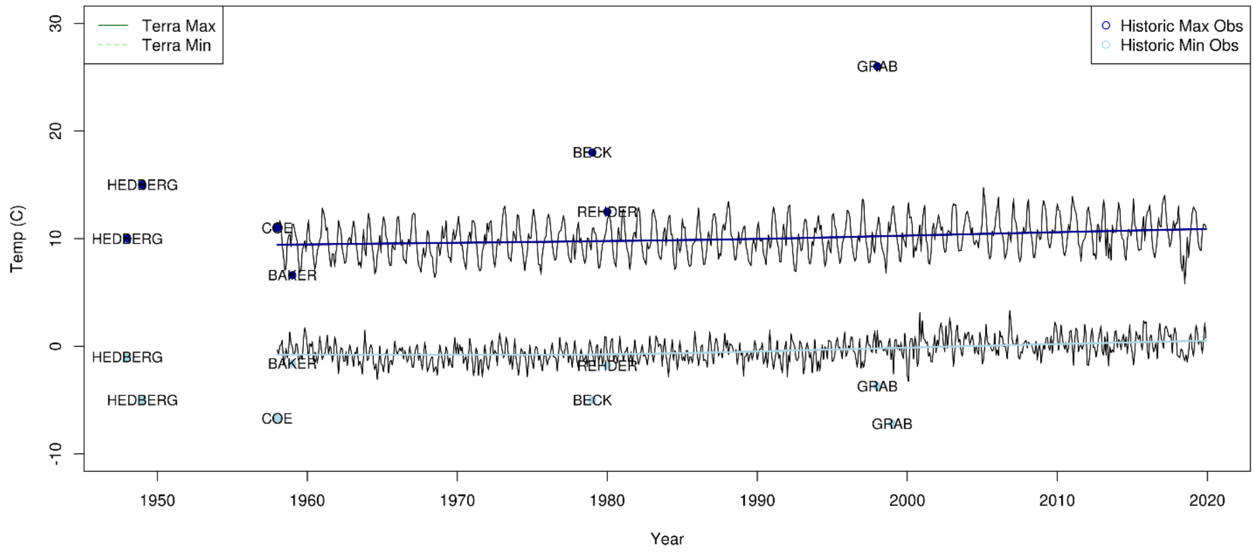

Figure C1-6 TerraCLimate minimum and maximum temperatures as compared to historical minimum and maximum temperatures over the time series

Precipitation data does not show any significant trend in monthly precipitation over the time series. However looking at the individual seasons, there appears to be more precipitation variability in the most recent bi-decade (2000-2020), with a higher range of values in the months of April and October.

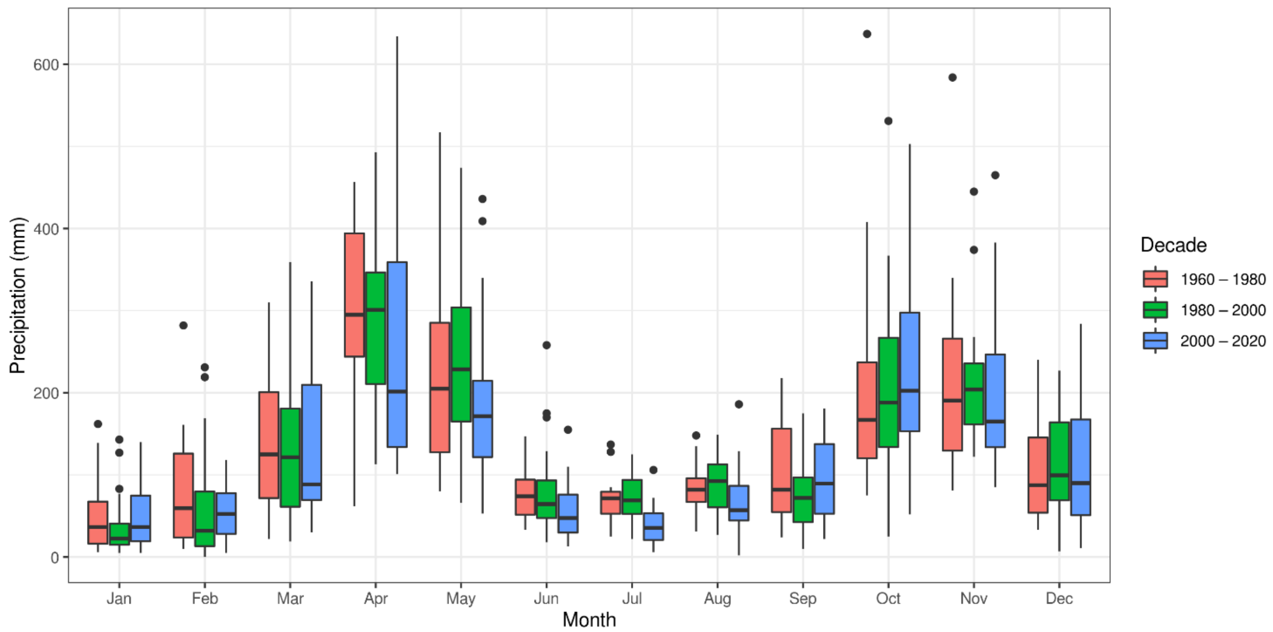

Figure C1-7 Seasonal trends in precipitation at Met Station from TerraClimate data

C1.4 Temperature patterns by mountain

Mount Kenya and Mount Elgon exhibited similar diurnal and seasonal temperature patterns, although they were more pronounced in Mount Elgon. A comparison of daily and monthly mean temperatures at 4000 m shows this difference. There is a steeper parabolic curve for daily temperatures at Mt. Elgon than Mt. Kenya, with noticeably higher mean temperatures at 10-11am, but similar night-time mean temperatures. The monthly means were higher for every month except for October, when they were roughly the same. Some of this could be explained by overheating of the temperature loggers (See Appendix C5), which may have been more of a factor on Mount Elgon than Mount Kenya. While this mostly affects maximum temperatures, it may in turn affect averages as well. Conversely this may just be a function of differences in solar radiation due to topography and aspect.

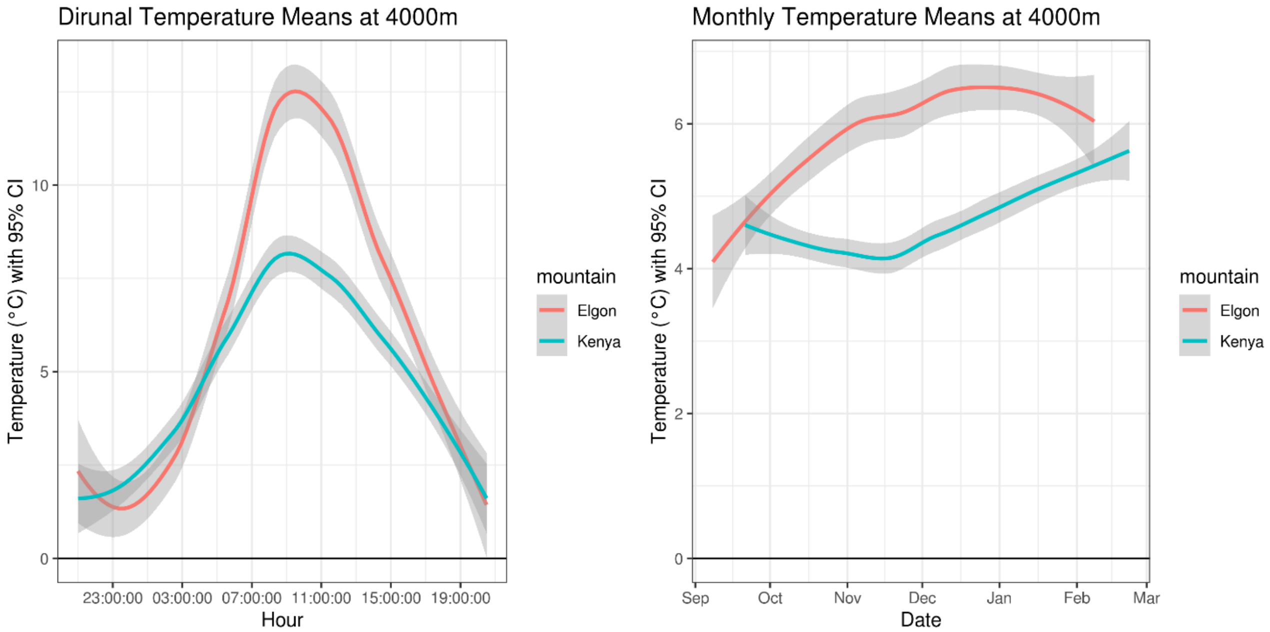

Figure C1-8 Diurnal and monthly mean temperatures with 95% confidence intervals at 4000 m in Mount Elgon and Mount Kenya

For minimum temperatures, the daily pattern is similar for both mountains, but Mount Elgon had lower night-time minimum temperatures than Mount Kenya. Seasonally, there's a strange divergence, with similar monthly minimums from September-December, and then noticeably lower minimums in January-February. Minimum temperatures are generally unaffected by temperature logger positioning (see Appendix C5). These differences then are likely a function of differing topography. The lower minimums at Mount Elgon suggest cold pockets were cool air pools. The difference by month points to slight changes in solar angle. Mount Elgon is slightly more north of the equator than Mount Kenya and may get vestiges of northern seasonal patterns. Even Mount Kenya, which is virtually on the equator, receives changes in sun angle throughout the year (Young, 1984). These slight changes in solar angle during the year are likely amplified in the moorland with less atmosphere to buffer climatic extremes.

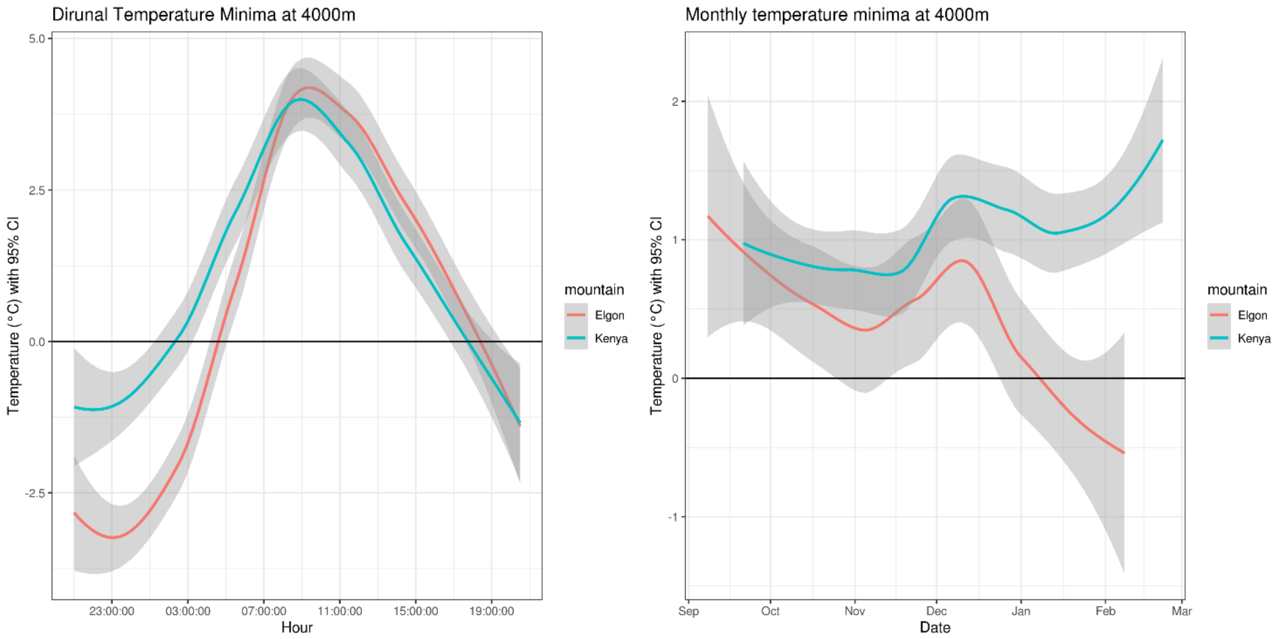

Figure C1-9 Diurnal and monthly minimum temperatures with 95% confidence intervals at 4000 m in Mount Elgon and Mount Kenya

C1.5 Hobo loggers and direct radiation

The suspiciously high maximum temperatures in some of the loggers in this study suggest potential overheating from direct radiation from the sun. Hobo Pendant loggers are susceptible to overheating in the sunlight, if they are not placed in the shade. Despite efforts to place all the loggers in the shade, it was not always possible to ensure adequate shade cover throughout the day. This was particularly the case on Mount Elgon, where values in excess of 40°C were sometimes recorded. This makes comparisons with historical data tricky, as authors rarely recorded in detail where they placed the loggers or the specific tolerances of their loggers. In particular the high readings from Grab et al. (2004) in Teleki valley, are likely artefacts.

A comparison of temperatures at the 3600 m contour, with a radiation shield and without, shows temperature data was affected. In Mount Elgon in particular, maximum temperatures were significantly higher in the logger without the shield (two-tailed t-test: ($t(306)= 14.091$; $p <0.0001$). Interestingly, however, minimum temperatures were also lower ($t(306)=-10.085$, $p<0.0001$). Perhaps shield served to insulate the logger from cold extremes as well. For Mount Kenya, however, while daily maximums were significantly higher for the logger without the shield (two-tailed t-test: ($t(308)= 7.702$; $p = <0.001$), minimum temperatures were not any different ($t(308)=0.332$; $p = 0.740$). From the raw data, it can be seen that the extent of the higher warming on the shield-less logger varied very much from day to day.

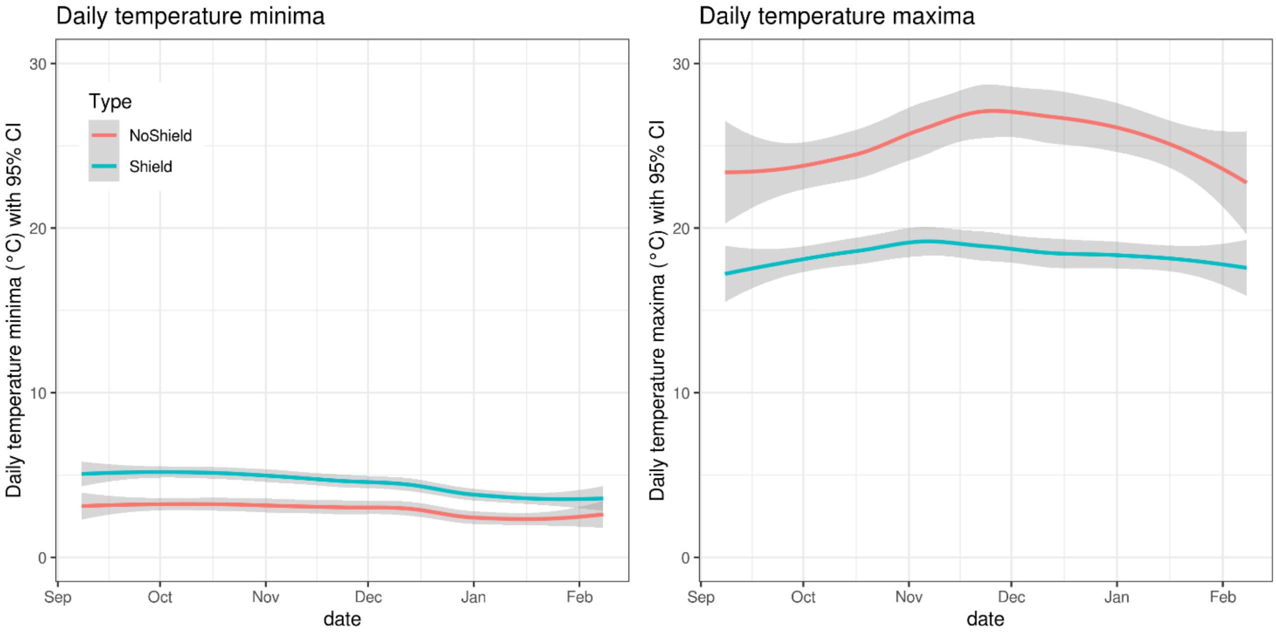

Figure C1-10 Monthly mean temperatures with 95% confidence intervals at 3600 m on Mount Elgon with and without a radiation shield

The highest elevation logger in Mount Kenya (4200 m) and on Mount Elgon (4100 m) also displayed suspiciously warm temperatures. However this is less likely to be due to direct radiation and more likely due to re-radiation from the rocks. In particular, the 4200 m logger on Mount Kenya was placed under a rock- blocked completely from direct radiation- and yet its temperature readings were warmer than the 4000 m logger for parts of the year despite the 200 m difference in elevation between the two. The monthly temperature pattern for the two loggers is interesting: from November to February the temperature warms up to hotter than the 4000 m logger, but then decreases again from March- October with temperatures in line with what would be expected. November to December is the dry season- and all loggers show a warming during this time, followed by a cooling for the rest of the year. It is likely that this warming is magnified for the case of the 4200 m logger as the rocks re-radiate that heat back onto the logger causing excess temperature readings.

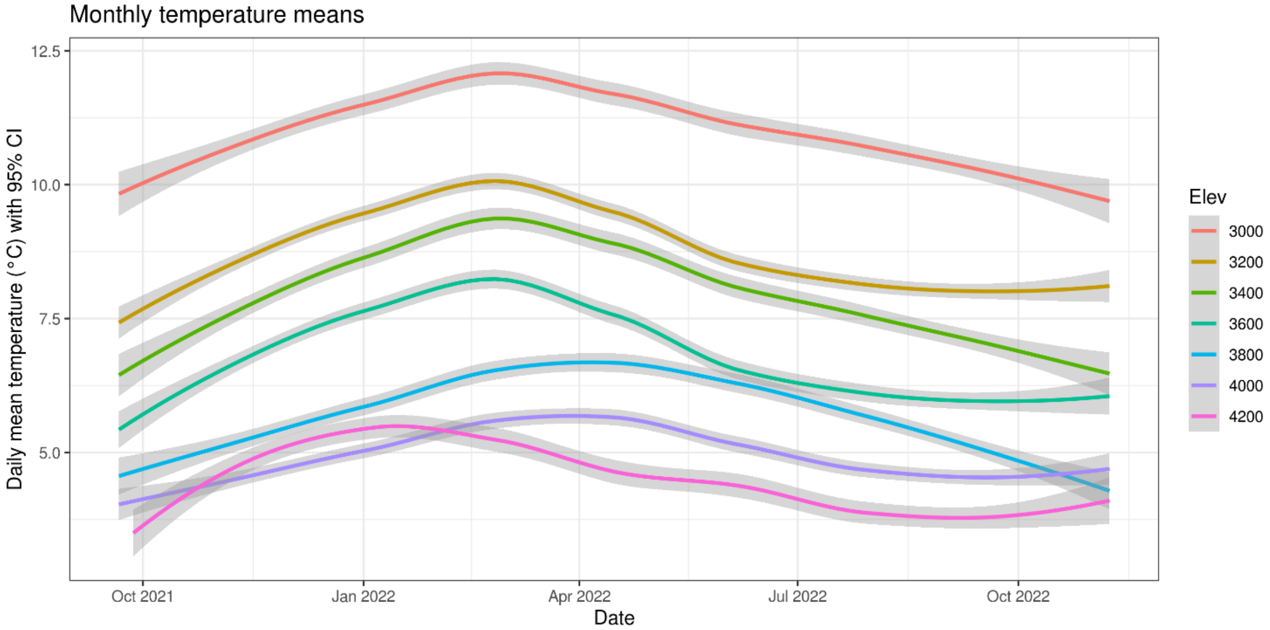

Figure C1-11 Mean monthly temperatures with 95% confidence intervals for the 7 data loggers on Mount Kenya

C2. Soil and Vegetation

C2.1 Soil properties- patterns with elevation

Soil properties on Mount Kenya and Mount Elgon, generally did not display any relationship with elevation. At each elevation only one sample was taken (a homogenized sample), so it was not possible to calculate the variability at each elevation. Nonetheless, for the cations as well as nitrogen and carbon, there was no noticeable pattern. Calcium values were much higher on Mount Elgon than Mount Kenya, but otherwise most cations were found at levels of around 0.5-3 meq %.

Soil properties generally fell within the range of historically reported values for comparable elevations. Looking just at the Mount Kenya data, for which there is a wealth of historical data, there is overall similarity in most of the soil properties. The biggest difference is for soil nitrogen which was significantly lower in the current study than in historical studies. While soil carbon was overall similar to historic records, soil nitrogen was uniformly lower across all elevations.

Table C2-1 Soil properties in Teleki Valley, Mount Kenya as compared to historical studies (top 15cm unless indicated and Teleki Valley unless indicated)

Author	**Elevation (m)**	**PH**	**Na (meq%)**	**K (meq%)**	**Ca (meq%)**	**Mg (meq%)**	**Carbon (%)**	**Nitrogen (%)**	**Phosphorus (ppm)**
Current Study	3200	4.3	0.86	0.32	0.8	1.41	6.34	0.48	48.9
Current Study	3400	4.7	0.52	0.1	0.4	1.42	6.48	0.5	68.4
Current Study	3600	6.1	0.34	1.04	5.4	2.42	3.68	0.32	34.7
Current Study	3800	4.5	0.42	0.58	0.4	4.25	20.7	0.7	44.2
Current Study	4000	4.3	0.44	0.54	0.4	1.45	15.1	0.58	65.3
Current Study	4200	5.0	0.88	1.02	0.8	2.11	2.6	0.22	29.7
Speck, 1982	4110	5.1					6	0.5	

Speck, 1982	3960	5.4	0.9	1.4	5	2.5	6.12	0.72	
Speck, 1982	3410		0.1	0.6	1.4	0.7	6.8	0.83	
Speck, 1982	3940	5.4	0.1	0.1	1.3	0.7	3.8	0.52	
Young, 1984*	4190		0.17	0.04	2.7	0.87	7.9	0.77	122
Young, 1984*	4200		0.32	0.05	5.05	1.66	8.4	0.89	84
Young, 1984*	4190		0.44	0.08	2.2	0.48	7.5	0.64	76
Young, 1984*	4100		0.46	0.42	2.05	1.8	9.9	0.93	42
Young, 1984*	4000		0.57	0.29	2.4	2.31	15.5	1.63	42
Young, 1984*	3970		0.57	0.32	1.45	1.23	13.3	1.31	32
Coe, 1967+	4175	5.2	0.2	0.3	0.4	0.6	8.8	0.73	52
Coe, 1967+	4175	5.2	0.3	0.4	1.6	1.8	12.6	1.1	58
Mahoney & Boyer, 1987	4180	4.8	0.22	0.47	1.44	0.36	13.7	0.83	
Mahoney & Boyer, 1987	4175	4.5	0.2	0.54	0.84	0.35	13.2	0.52	
Mahoney & Boyer, 1987	4170	4.8	0.47	0.46	3.34	0.24	10.7	0.97	

** Depth not indicated   + Mackinders Valley, Mount Kenya*
(Coe, 1967; Mahaney & Boyer, 1987; Speck, 1982; Young, 1984)

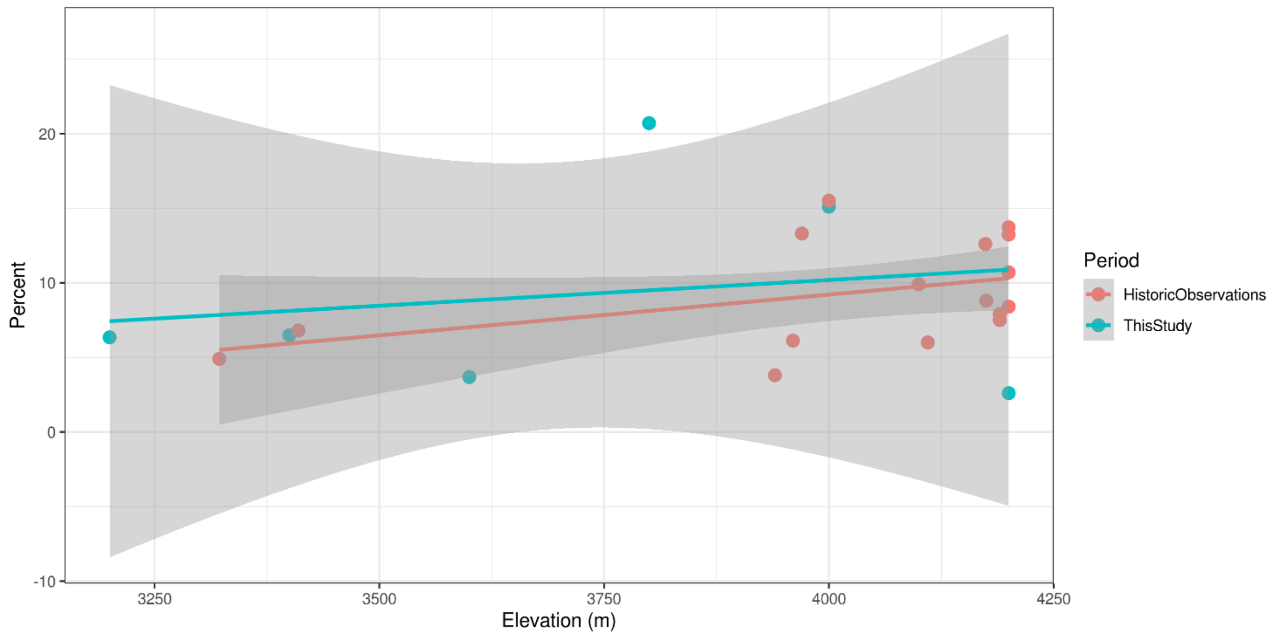

Figure C2-1 Comparison of soil carbon by elevation in the current study as compared to historic observations

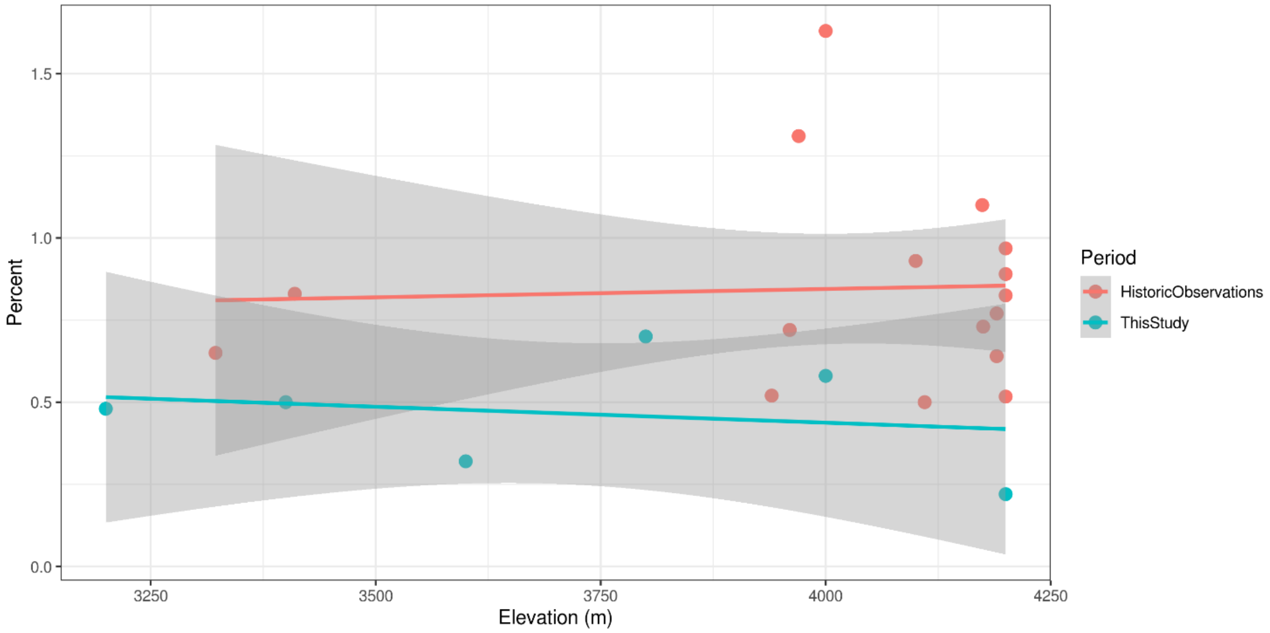

Figure C2-2 Comparison of soil nitrogen by elevation in the current study as compared to historic observations

C2.2 Plant-plant interactions associated with Dendrosenecio keniodendron

The Canonical Correspondence Analysis (CCA) for 1980 and 2021 indicated that *D. keniodendron* density was the second biggest contributor to plant community composition after elevation and live vegetation cover (moisture). The authors of the 1980 study noted the influence of *D. keniodendron* on the shrub communities of *Alchemilla* and *Helichrysum*, and noted the opposite influence on these two- a pattern also apparent in 2021. A Non-metric Multidimensional Scaling (NMDS) of the plant communities in 2021, however, shows that there are other taxa associated with D. keniodendron as well, including *Valeriana kilimandscharica, Senecio purtschelleri, Carduus platyphyllus,* and *Lobelia telekii. Lobelia teleki* is known to occur alongside *D. keniodendron* in the upper slopes, but the impact on these other species is not known. As these other species are generally small, prostrate plants, it is likely that *D. keniodendron* serves as a nurse plant for them, protecting against the harsh climate to allow them to establish.

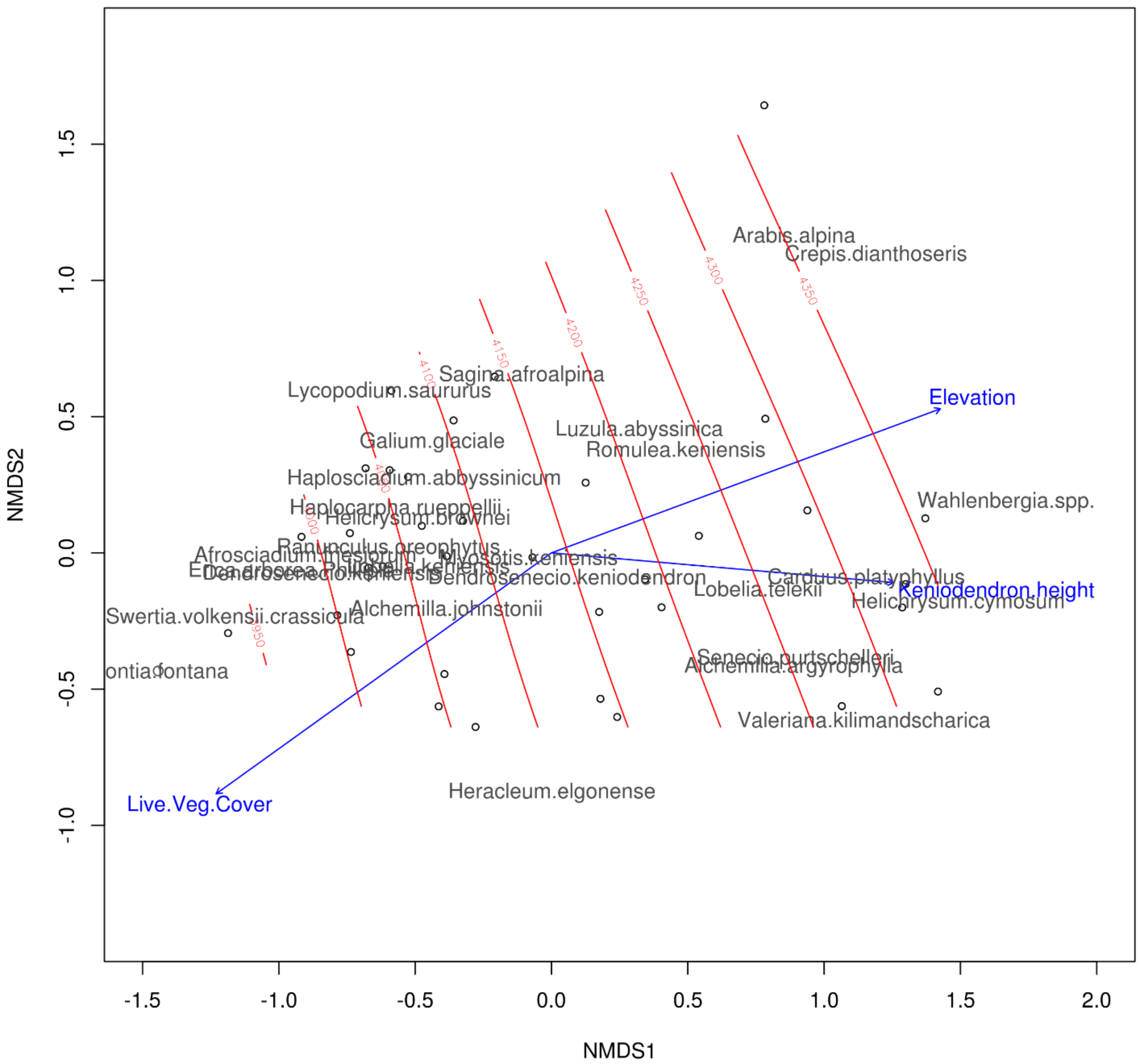

Figure C2-3 Non-metric multidimensional scaling (NMDS) plot with the three dominant variables and elevation contours

C2.3 Plant abundance according to aspect- north vs. south valley wall

The 1980 study by Young and Peacock (1992) separated out the valley positions according to aspect- north and south aspect. They found, however, little difference according to aspect, which is not surprising given it is an East-West valley located along the equator. The current study also initially separated the sample plots by aspect, but then pooled the samples in order to increase the sample size. Breaking out by aspect does show some slight differences, although not significant. Even pooling the data for both periods, there is little difference by aspect: *D. keniodendron* had slightly lower abundances on the south aspect ridges and slopes, but not in the valley.

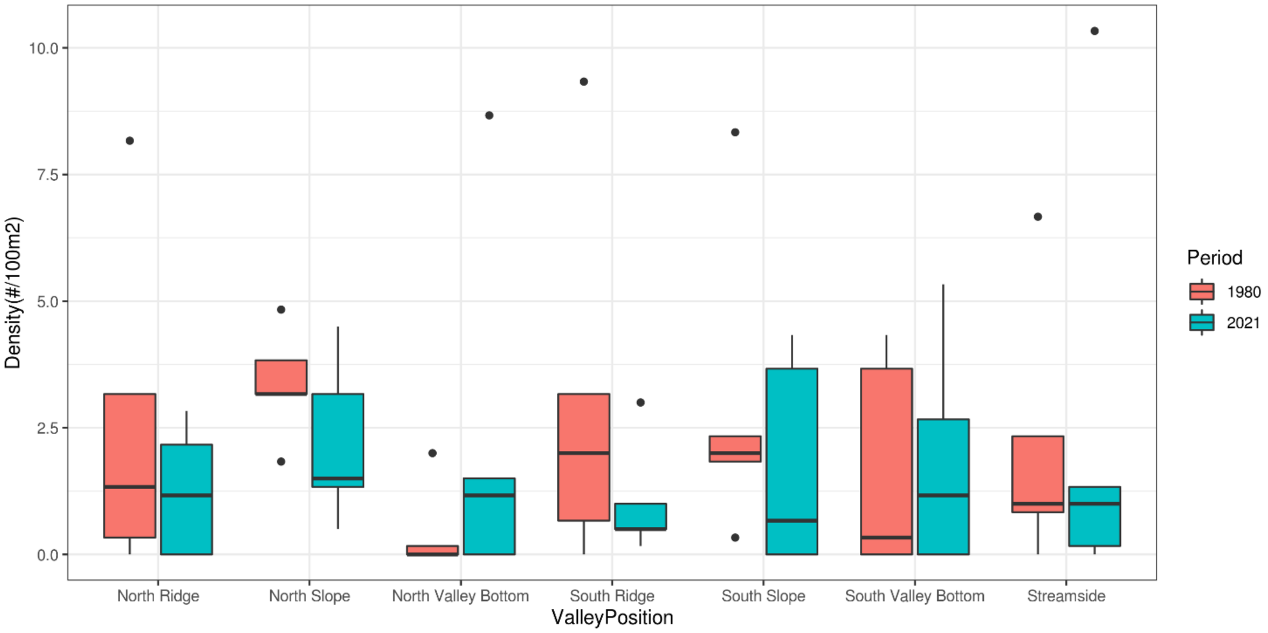

Figure C2-4 Dendrosenecio keniodendron *density valley position in Teleki Valley in 1980 and 2021*

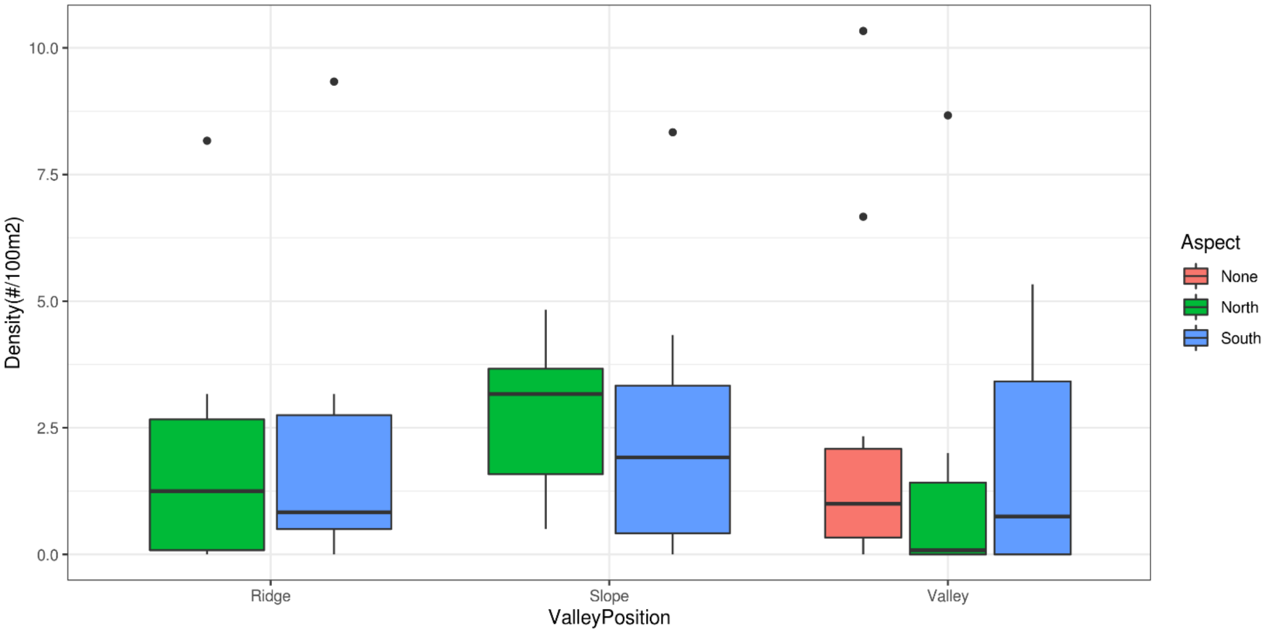

Figure C2-5 Dendrosenecio keniodendron *density by aspect and valley position in Teleki Valley*

<u>C2.4 Elevation ranges of Giant Rosettes on Mount Kenya</u>

Olov Hedberg had documented elevation ranges for the Giant Rosettes across all the East African Mountains (Hedberg, 1957). For Mount Kenya, the lowest elevation that he was able to find the two species of Lobelia were 3450 m and 3850 m, which is very similar to the lowest elevations found in this study. Hedberg recorded the ranges of both species as potentially as low as 3050 m according to his sources, but he was not able to personally verify this. For the *Dendrosenecios,* the ranges reported by Hedberg, and then again by Knox (2005) were slightly lower than what was found in this study. The lowest elevation for *D. keniensis* in both studies was 3300 m, whereas this study did not find one until 3460 m. For *D. keniodendron* the values were 3650 m for Knox, 3800 m for Hedberg, while this study did not find an individual until 3900 m. These very preliminary results could suggest upward movement of the *Dendrosenecios*, but these values would need to be confirmed at different aspects on the mountain.

Table C2-2 Lowest elevation- in m.a.s.l- for the main giant rosette species on Mount Kenya

Species	**Hedberg, 1957**	**Knox, 2005**	**Downing, 2021**
Lobelia keniensis	3450		3480
Lobelia telekii	3850		3900
Dendrosenecio keniensis	3300	3300	3463
Dendrosenecio keniodendron	3800	3650	3900

C3 Human Dimension

<u>C3.1 Impact of study area on perceptions</u>

The respondents around Mount Kenya had different demographic characteristics than those from Mount Elgon, reflecting the different underlying socio-economic situations. There were more immigrants around Mount Kenya- those having moved to the area, whereas in Mount Elgon the majority had been born in the area and had remained there. This may suggests that the Mount Kenya area has more job opportunities attracting people from neighbouring counties. It also indicates a closer connectedness to the outside world for the Mount Kenya communities.

The respondents in Mount Elgon were more likely to be farmers and with a primary-school level of education. Nevertheless the socio-economic status- occupation and education- of those moving into the area was not substantially different from the locals in either study area. This indicates that the effect of immigrant status on perceptions has to do with a connectivity with the environment rather than underlying socio-economic factors.

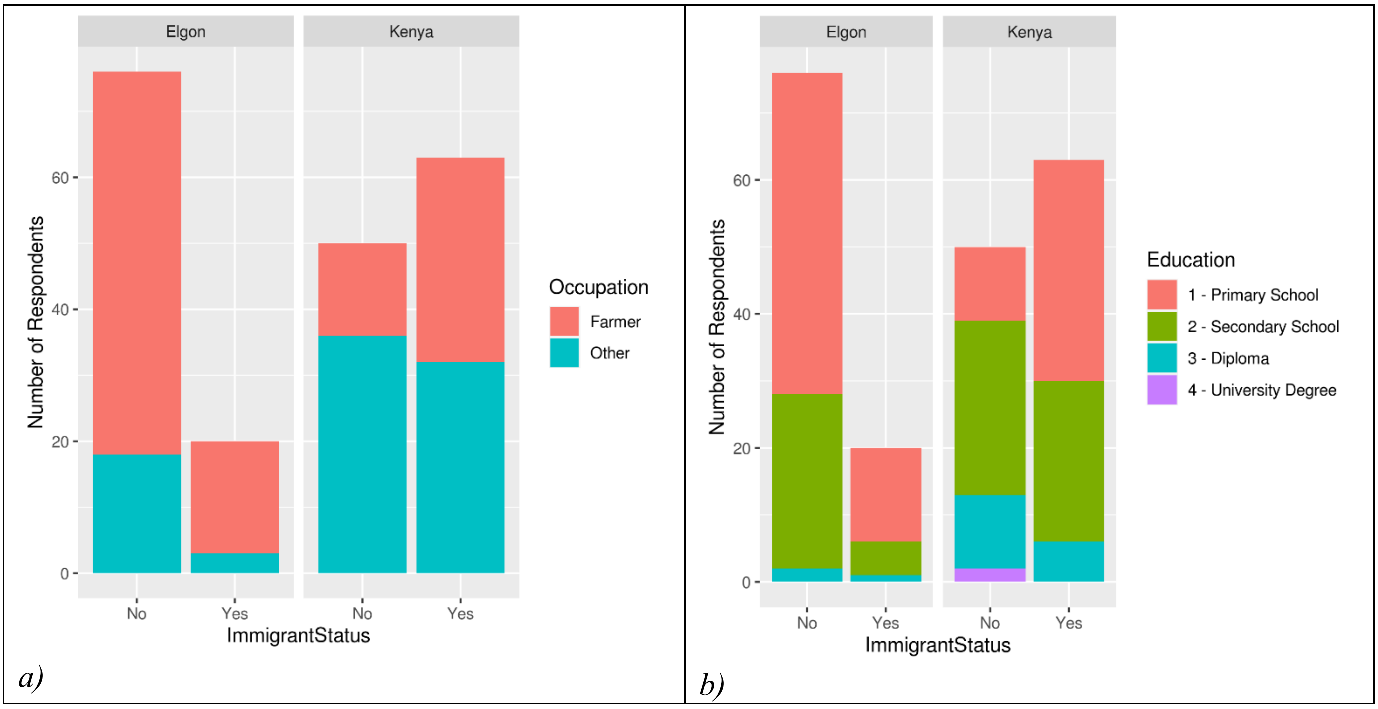

Figure C3-1 Immigrant status compared with a) occupation and b) education for questionnaire respondents in Mount Kenya and Mount Elgon

Although perceptions were different between Mount Kenya and Mount Elgon, the magnitude of this difference when averaged for both study areas was quite small. Those in Mount Elgon had a closer connection to the mountain- visiting it more frequently and rating its importance in their life higher. They therefore also rated the provision and regulating services of the mountain higher, and overall rated the utility higher. The Utility of the mountain was a combination of agreement to three statements regarding utility and availability of mountain resources, namely:

- The mountain and its resources are important in my everyday life
- Mountain resources are free and available to all
- The mountain has additional value beyond what my community gains from it

Nevertheless the respondents from Mount Kenya overall ranked the Vulnerability of the mountain higher. Vulnerability was a combination of agreement to three statements regarding changes mountain resources, namely:

- The mountain is vulnerable to climate change
- Services provided by the mountain have declined in availability over the years
- I fear that mountain resources may be lost forever if climate changes continue

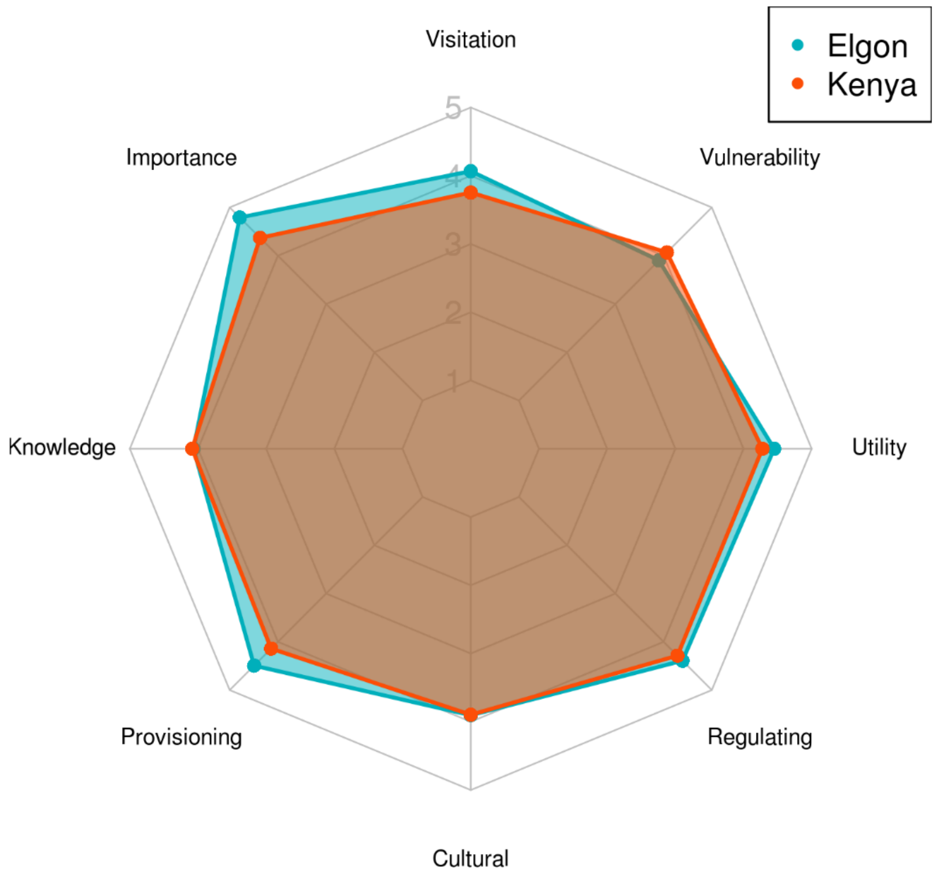

Figure C3-2 Spider diagram for interaction and views on mountain resources by study area (shown are mean likert scores for each study area)

The differences between the two communities is also seen in the issues that were of importance to them. This can be illustrated by a word cloud of the transcripts from the interviews and focus group discussions. In Mount Elgon, the most common words used (outside of basic filler words- and, the, etc.) were ‘forest’ and ‘trees’, whereas in Mount Kenya they were ‘water’ and ‘people’. Respondents around Mount Kenya were particularly concerned about issues of water and how that was affecting the people surrounding the mountains. The Mount Elgon communities had a broader appreciation of the full range of ecosystem services provided by the mountain.

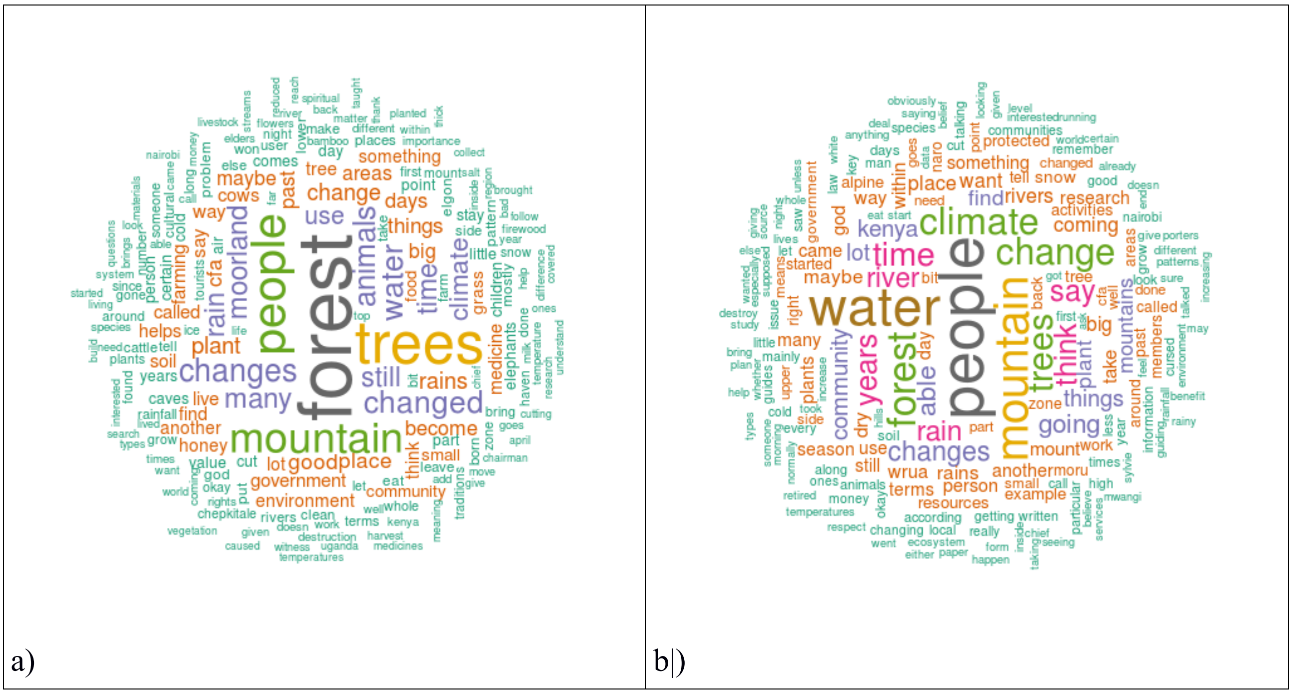

Figure C3-3 Word clouds of focus group transcripts in a) Mount Elgon and b) Mount Kenya

<u>C3.2 Example quotations for environmental changes observed</u>

Respondents from the Interviews and Focus Group Discussions had interesting examples of environmental changes that they had experienced during their lifetimes. Some were attributable to a global climate change phenomenon, whereas others were more related to local land degradation. Others, however, saw no little to no change in their environment, or if there was any change it was a positive one.

Table C3-1 Example quotations illustrating environment changes observed by local communities

	Attribution of Change		
	Global Climate Change	**Local Land Degradation**	**No Change/Positive Change**
Vegetation	"Another thing, I have seen like funny funny plants coming up. Like, I was in Letudo last week, and you realize pine trees are naturally germinating in the mountain at nearly 4000 meters. And it's funny to see a pine tree just growing there. And yeah, so it's getting warmer." (FGD #2, Mt. Kenya)	"Even I can say where they have cut trees... we used to have Elgon Teak, and you know Elgon Teak is called Elgon Teak because Elgon is the only place where these teaks were found. So these days there are none- there are none." (FGD #1, Mt. Elgon)	"Ah there's no difference, trees are just okay." (FGD #2, Mt. Elgon)
Wildlife	"Even the animals. We are experiencing some animals that you could not find here. Yeah, mostly the birds. I've seen Tulika very low and it should not be getting lower than 2600 meters". (FGD #2, Mt. Kenya)	"... there was some green snakes moving along the paths...they are no longer there. There's no fish, we used to have crabs, they are no longer there, why? Because when the river dries up... and that water is now pumped out by farmers and the river is left bare- those natural species that were meant to be along the river [are no longer]." (FGD #1, Mt. Kenya)	"The animals are full. These days the forest is full of them. Even if people go inside [the forest], they are fearful of them- and in the past there was no such fear. Because elephants are many, even in the afternoon you can find them in this area nearby. Hyenas, buffaloes- in the past you wouldn't have been able to see them like this." (KII #2, Mt. Kenya)
Soil	"There is something called solifluction where the night freezing creates some ice needles that pushes down from clouds, and in that way that's how you can notice whether it's getting colder or warmer. For example, in January... it took us like two weeks before we [were] spotting or experiencing any soliflucted day." (FGD #2, Mt. Kenya)	"Even here up above if you walk you'll see landslide, an area where it rains abnormally because of this forest destruction. You get again soils have been cut away and covered other areas....as I said because of cutting trees, it is a huge harm for the country." (FGD #1, Mt. Elgon)	N/A
Air Quality	N/A	"And when they plant to replace, they replace with foreign trees- exotics are planted there. So that what we said, that natural environment that used to be there in the time of our grandparents is lost. And you know this foreign air....brings bad diseases here.." (FGD #1, Mt. Elgon)	"The air itself isn't bad- it's clean. The air is clean it hasn't broken down." (KII #1, Mt. Elgon)
Temperature	"When I started mountaineering, the level of glaciers was like very high and currently it has receded in my eyes. And, with that is leading to weathering, for example, right now, if you take Naro Moru route to the peak, there is a certain area where they were forced to install [support] ladders as for glaciers are receding." (FGD #2, Mt. Kenya)	"Because we are now nearing the peak of the mountain, and yet now here on the slopes, we've done some small destruction, and the climate has changed. Even if at the top of the mountain, you'd find there's a small difference- not as before. Because in those days, if you reach the peak, you start shivering. But now, you can still climb and don't see that." (KII #1, Mt. Elgon)	"First of all, now is good. If it was the time of rains, the coldness is fierce, this whole area would just be water..." (FGD #2, Mt. Elgon)

Rain Pattern	"There used to be rain in the morning, there used to be rain in the evening, the water was in plenty. But now I don't remember when I had rains in the morning.... And even when the rains come, they come in a form like the rains were not formed [previously]: in hailstones." (FGD #1, Mt. Kenya)	"And then another problem, you know the rain used to come very slowly. If it comes from over there...it comes slowly, slowly until it passes. But now you see the wind over there, and you're surprised by water raining down mixed with hail, because there's no trees to hold the flow of the rain steady." (FGD #1, Mt. Elgon)	"Oh here it hasn't changed. If you guys had come during the rains, you wouldn't have made it. Your motorcycle would give up the hard work down there. April if it rains- first rains come here very big..." (FGD #2, Mt. Elgon)
Rain Seasons	"So what I would say is I cannot plan what I'm doing on the mountain, looking at the seasons that used to be there. Totally destabilized. When you think it won't rain, it rains, when you think it will rain it doesn't rain. It's no longer as easy as it used to be- people will think- I'm going to plant at this time, and I'll benefit from that rain. These days, you just have to wait for it to happen." (KII #1, Mt. Kenya)	"But thereafter- thereafter, as we continued the life- the pattern of climate change has changed because the number of trees has been reduced to the extent that the amount of rain also, and the period- the pattern of rain has changed. The pattern of rain has changed that like at this season we could be having rain, but now we may go up to April. So the pattern of rain has changed." (KII #1, Mt. Elgon)	"...change normally in this area comes after every 10 years. We have experienced [it in] 1984, 1994, 2004, 2014, and now we are expecting and we have seen the signs of climate change- 2024." (FGD #1, Mt. Kenya)
Water Quality/ Quantity	"All sides, the tarns are sinking. You can find the level, or maybe where it's somehow flat. You can even note with your eyes like some years back the level of the water was this area, and now you find that the tarn, the glacial lakes I mean, they are becoming smaller meaning that the water is [reduced]." (FGD #2, Mt. Kenya)	"One point I'm seeing is rainfall has become very low... we have low volume of water. Why do I say so? Because the forest has become cleared, so water has reduced. You know the water in the past could carry even an elephant. In this terrain it could carry even an elephant. For now it has reduced because forests have been cleared for the purpose of farming, and issues of fuel- people cutting haphazardly." (FGD #1, Mt. Elgon)	"Here water is very clean, no problems. If you look in the streams- you can see to the rocks down below- you might think it's very close- very clean." (FGD #2, Mt. Elgon)

APPENDIX D: Raw Data Tables

D1- Temperature data- Mount Kenya 4000 m

No.	longdate	min_temp	max_temp	mean_temp	range
1	9/21/2021	1.84	9.18	5.31	7.34
2	9/22/2021	1.33	11.45	4.57	10.12
3	9/23/2021	0.34	10.29	4.68	9.95
4	9/24/2021	1.2	10.98	5.30	9.78
5	9/25/2021	0.68	7.03	3.62	6.35
6	9/26/2021	-0.13	8.02	3.27	8.15
7	9/27/2021	0.68	8.83	4.42	8.15
8	9/28/2021	-1.16	7.55	2.38	8.71
9	9/29/2021	-0.82	11.67	4.89	12.49
10	9/30/2021	0.17	10.68	4.43	10.51
11	10/1/2021	2.06	9.69	4.67	7.63
12	10/2/2021	0.73	8.83	4.14	8.1
13	10/3/2021	-0.22	7.81	3.12	8.03
14	10/4/2021	-0.26	9.26	4.23	9.52
15	10/5/2021	1.67	10.38	5.44	8.71
16	10/6/2021	1.54	9.78	5.27	8.24
17	10/7/2021	0.51	8.53	4.44	8.02
18	10/8/2021	2.74	9.14	5.55	6.4
19	10/9/2021	2.44	10.08	5.32	7.64
20	10/10/2021	1.84	10.34	5.57	8.5
21	10/11/2021	1.37	11.37	4.88	10
22	10/12/2021	0.98	9.09	4.77	8.11
23	10/13/2021	1.76	7.03	4.32	5.27
24	10/14/2021	0.64	7.12	3.98	6.48
25	10/15/2021	0.6	6.9	3.77	6.3
26	10/16/2021	0.3	8.23	3.71	7.93
27	10/17/2021	1.97	7.85	4.27	5.88
28	10/18/2021	1.28	8.32	4.17	7.04
29	10/19/2021	1.93	7.89	4.60	5.96
30	10/20/2021	2.36	5.7	4.10	3.34
31	10/21/2021	1.41	7.2	3.72	5.79
32	10/22/2021	1.11	9.14	4.45	8.03
33	10/23/2021	0.98	7.33	3.77	6.35
34	10/24/2021	0.3	11.19	4.73	10.89
35	10/25/2021	0.25	9.18	4.59	8.93
36	10/26/2021	1.11	11.84	5.62	10.73
37	10/27/2021	1.41	9.74	4.83	8.33
38	10/28/2021	1.33	9.05	4.53	7.72
39	10/29/2021	0.81	9.18	4.21	8.37
40	10/30/2021	1.03	9.48	4.59	8.45
41	10/31/2021	1.71	10.12	4.79	8.41
42	11/1/2021	0.3	7.25	3.69	6.95
43	11/2/2021	0.38	9.14	3.98	8.76
44	11/3/2021	-0.26	7.76	3.41	8.02
45	11/4/2021	0.73	8.53	4.06	7.8
46	11/5/2021	-0.05	8.71	4.12	8.76
47	11/6/2021	0.34	9.65	4.60	9.31
48	11/7/2021	1.54	10.16	4.85	8.62
49	11/8/2021	-1.55	8.79	3.35	10.34
50	11/9/2021	0.25	9.86	4.68	9.61
51	11/10/2021	1.84	8.88	4.84	7.04
52	11/11/2021	1.03	11.32	5.00	10.29
53	11/12/2021	-0.6	10.64	3.84	11.24
54	11/13/2021	0.47	9.05	4.46	8.58
55	11/14/2021	-0.86	9.31	4.21	10.17
56	11/15/2021	1.07	8.88	4.48	7.81
57	11/16/2021	1.5	6.35	3.82	4.85
58	11/17/2021	0.43	8.62	3.88	8.19
59	11/18/2021	0.47	9.01	4.05	8.54
60	11/19/2021	0.08	9.44	3.32	9.36
61	11/20/2021	0.21	8.75	3.27	8.54
62	11/21/2021	0.77	9.44	4.46	8.67
63	11/22/2021	0	8.23	3.85	8.23
64	11/23/2021	1.37	11.19	4.02	9.82
65	11/24/2021	1.11	10.29	4.53	9.18
66	11/25/2021	0.86	12.22	4.62	11.36
67	11/26/2021	1.33	6.43	4.24	5.1
68	11/27/2021	1.93	5.96	3.57	4.03
69	11/28/2021	1.33	7.68	4.32	6.35
70	11/29/2021	2.53	7.85	4.84	5.32
71	11/30/2021	3.13	7.89	4.90	4.76
72	12/1/2021	1.54	6.05	3.45	4.51
73	12/2/2021	0.6	6.65	3.78	6.05
74	12/3/2021	1.46	6.99	4.57	5.53
75	12/4/2021	1.2	7.72	4.29	6.52
76	12/5/2021	0.04	6.86	3.50	6.82
77	12/6/2021	0.08	6.78	3.17	6.7
78	12/7/2021	-0.43	7.29	3.38	7.72
79	12/8/2021	0.77	8.36	4.24	7.59
80	12/9/2021	0.73	6.26	3.82	5.53
81	12/10/2021	2.14	7.33	4.51	5.19
82	12/11/2021	-0.17	8.28	4.20	8.45
83	12/12/2021	0.64	9.69	4.90	9.05
84	12/13/2021	2.27	10.08	5.06	7.81
85	12/14/2021	1.2	8.45	4.56	7.25
86	12/15/2021	0.77	6.56	3.85	5.79
87	12/16/2021	0.51	10.12	4.76	9.61
88	12/17/2021	1.58	10.21	5.20	8.63
89	12/18/2021	2.87	10.59	5.97	7.72
90	12/19/2021	3.69	9.86	6.17	6.17
91	12/20/2021	3.09	11.49	6.51	8.4
92	12/21/2021	2.1	9.05	5.39	6.95

93	12/22/2021	2.61	9.39	5.76	6.78
94	12/23/2021	3.69	10.34	6.44	6.65
95	12/24/2021	2.87	7.72	5.34	4.85
96	12/25/2021	2.61	7.03	4.89	4.42
97	12/26/2021	2.79	8.11	5.38	5.32
98	12/27/2021	1.24	9.82	5.34	8.58
99	12/28/2021	-0.09	7.72	3.95	7.81
100	12/29/2021	1.5	8.36	4.00	6.86
101	12/30/2021	1.46	8.53	4.35	7.07
102	12/31/2021	0.94	6.52	3.47	5.58
103	1/1/2022	0.3	7.46	3.69	7.16
104	1/2/2022	0.34	11.41	5.60	11.07
105	1/3/2022	0.68	10.68	5.11	10
106	1/4/2022	-0.56	9.95	4.53	10.51
107	1/5/2022	0.94	9.86	4.70	8.92
108	1/6/2022	0.68	9.35	4.68	8.67
109	1/7/2022	1.03	9.14	4.53	8.11
110	1/8/2022	-1.08	10.59	4.26	11.67
111	1/9/2022	-0.73	11.07	4.65	11.8
112	1/10/2022	-1.46	10.16	4.28	11.62
113	1/11/2022	0.21	13.12	5.61	12.91
114	1/12/2022	0.38	10.68	4.86	10.3
115	1/13/2022	-0.05	11.79	5.21	11.84
116	1/14/2022	1.41	12.05	5.92	10.64
117	1/15/2022	1.37	9.35	4.13	7.98
118	1/16/2022	1.8	8.41	4.80	6.61
119	1/17/2022	2.87	5.96	4.45	3.09
120	1/18/2022	0.94	7.63	3.93	6.69
121	1/19/2022	1.71	10.55	5.28	8.84
122	1/20/2022	-0.17	12.57	4.84	12.74
123	1/21/2022	1.07	9.14	4.40	8.07
124	1/22/2022	0.43	9.18	4.57	8.75
125	1/23/2022	0.34	11.19	4.83	10.85
126	1/24/2022	1.58	10.94	5.92	9.36
127	1/25/2022	0.64	10.81	5.08	10.17
128	1/26/2022	0.25	12.78	5.67	12.53
129	1/27/2022	-0.9	10.16	4.42	11.06
130	1/28/2022	0.47	12.4	5.16	11.93
131	1/29/2022	0.86	10.89	4.87	10.03
132	1/30/2022	0.6	13.38	5.98	12.78
133	1/31/2022	1.8	11.97	6.26	10.17
134	2/1/2022	1.88	9.48	5.51	7.6
135	2/2/2022	2.14	9.56	5.67	7.42
136	2/3/2022	2.27	12.61	6.29	10.34
137	2/4/2022	0.55	11.97	5.09	11.42
138	2/5/2022	-0.56	10.51	4.88	11.07
139	2/6/2022	2.74	13.25	6.30	10.51
140	2/7/2022	2.14	9.82	5.54	7.68
141	2/8/2022	1.16	13.47	6.43	12.31
142	2/9/2022	1.16	14.45	6.07	13.29
143	2/10/2022	1.2	12.7	5.97	11.5
144	2/11/2022	1.84	11.58	5.70	9.74
145	2/12/2022	1.88	13.51	5.98	11.63
146	2/13/2022	2.53	10.94	6.00	8.41
147	2/14/2022	1.71	14.33	5.33	12.62
148	2/15/2022	1.11	12.18	5.20	11.07
149	2/16/2022	0.73	12.82	5.70	12.09
150	2/17/2022	2.1	13.17	5.79	11.07
151	2/18/2022	0.73	11.75	4.59	11.02
152	2/19/2022	1.07	10.12	4.77	9.05
153	2/20/2022	1.37	11.97	5.78	10.6
154	2/21/2022	1.88	10.89	4.98	9.01
155	2/22/2022	3.13	10.46	5.89	7.33

D2- Species count data by transect- 2021

SPECIES/ TRANSECT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
Alchemilla johnstonii	10	9	10	10	10	10	10	10	9	7	10	10	7	10	6	4	9	9	10	1	6	6	0	0	4	10	0	9	6	0	0	5	10	7	0
Alchemilla argyrophylla	0	0	1	0	0	0	4	0	4	0	0	0	10	0	0	5	0	1	4	10	9	0	6	2	0	0	10	4	0	5	0	0	0	4	7
Cerastium spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Carduus platyphyllus	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2	1	0	1	0.5	0	1	1	2	0	0	1	0	0	1	0	0	0	0	2
Haplosciadium abbyssinicum	2	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0.5	0	1	0	0	0	0	0	0	0	1	0	0.5	2	0	0	0.5	0	0	0
Crepis dianthoseris	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	0	0	0.5	0
Sagina afroalpina	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0.5	0	0	0	2	0.5	0	6	0	0	0	0	0	0	0.5	0	0	0
Galium glaciale	1	0	0	0	3	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lobelia telekii	0	0	0	0	0	0	0.5	1	2	0	0	0	0.5	0	0	3	6	0	1	3	1	2	3	2	0	0	6	3	0	0	0	1	0	5	0
Lobelia keniensis	1	4	3	2	2	1	2	4	1	9	3	2	0	8	6	1	1	4	7	0	3	2	0	1	1	0	0	1	4	0	0	2	0	0	0
Dendrosenecio keniodendron	0	0	0	0	0	0	0	0	0	0	0	0	1	2	1	0	3	0	0	0	0	4	0	2	4	2	0	3	2	0	0	1	1	3	0
Senecio keniophytum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0
Senecio purtschelleri	0	0	0	0	0	0	0	0	0	1	0	0	0.5	0	0	0	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0.5	6
Dendrosenecio keniensis	1	7	0	6	6	4	1	7	0	2	5	7	0	0	3	0	0	2	1	0	0	0	0	0	0	1	0	0	1	0	0	2	0	0	0
Luzula abyssinica	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0
Haplocarpha rueppellii	0	2	10	1	4	1	7	8	0.5	0	10	10	0	0	9	0	0	7	4	0	0	7	0	0	7	0	0	0	10	0	0	10	1	0	0
Romulea keniensis	6	0	0	0	0	0	0	1	1	0	0	0	0	0	0	5	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	1	0
Helicrysum brownei	1	0	7	1	3	0	5	3	0	1	5	5	0	0	1	0	0	1	2	0	0	0	0	0.5	0	0	0	0	0	1	0.5	0	0	0	0
Helichrysum cymosum	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0.5	0	0	0	0	0	0	10	0	0	0	1	0	0	5	0	0	0	0.5	0
Subularia monticola	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Arabis alpina	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0	0	0	0	1	0	0	0	0	0	0	2	0	0	0.5	0
Lycopodium saururus	1	0	0	0	0	0	0.5	1	0	0.5	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0.5	0	0	0	0	0	0
Limosella africana	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Ranunculus oreophytus	5	0	0	2	0	0	4	4	0	1	1	8	0	0.5	3	0	0	6	2	0	0	1	0	0	0	6	0	0	3	0	0	0.5	1	0	0
Valeriana kilimandscharica	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wahlenbergia spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0
Crassula granvikii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Myosotis keniensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oreophyton falcatum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Swertia spp.	1	0.5	0	2	2	7	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Geranium arabicum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Heracleum elgonense	0	0	0	0	0	0	0	0	0	0	0	0	0.5	1	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Alchemilla cyclophylla	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cardamine obliqua	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Montia fontana	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Erica spp.	0.5	0	8	0	9	8	1	2	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Afrosciadium friesiorum	0	0	0	3	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

D3- Environment data by transect- 2021

Transect #	Position2	Position	% Rock	% Live Veg	Rehder Plant Community	Keniensis density	Keniodendron density	Elevation (m.a.s.l	Slope (deg)	Aspect	PLR	Kenio height (m)	NS Aspect	EW Aspect
1	Riverside	Valley Bottom	3	92.5	K- D. keniensis/ L. keniensis	150	8	3905	32.30	6.98	0.89	1.00	0.04	0.30
2	North Ridge	Ridge	0	94.5	K- D. keniensis/ L. keniensis	400	0	3969	24.68	224.56	N/A	0.00	0.03	0.33
3	South Ridge	Ridge	4	94.5	F- Philippia/ D. keniensis	10	3	4010	15.82	239.71	0.70	0.50	1.00	0.50
4	North Valley Bottom	Valley Bottom	0.5	99.5	K- D. keniensis/ L. keniensis	260	9	3879	13.37	338.63	0.83	0.61	0.06	0.27
5	South Valley Bottom	Valley Bottom	1	98	F- Philippia/ D. keniensis	150	0	3905	32.30	6.98	0.69	0.00	0.93	0.75
6	South Slope	Slope	0	99	F- Philippia/ D. keniensis	250	0	3983	28.08	4.14	0.93	0.00	0.91	0.78
7	North Slope	Slope	0	99	K- D. keniensis/ L. keniensis	81	8	3921	22.89	237.06	0.79	1.00	0.03	0.33
8	Riverside	Valley Bottom	2	97.5	K- D. keniensis/ L. keniensis	140	0	4002	32.85	349.80	0.87	0.00	0.95	0.71
9	North Ridge	Ridge	0	91.5	O- L. telekii/ D. keniodendron	0	17	4150	21.22	217.75	0.64	1.29	0.00	0.48
10	South Ridge	Ridge	5.5	84.5	K- D. keniensis/ L. keniensis	98	1	4142	9.19	279.32	0.74	0.50	1.00	0.50

11	North Valley Bottom	Valley Bottom	4.5	89.5	K- D. keniensis/ L. keniensis	250	0	3977	16.16	331.50	0.90	0.00	0.02	0.37
12	South Valley Bottom	Valley Bottom	3	94	K- D. keniensis/ L. keniensis	300	0	4002	32.85	349.80	0.81	0.00	0.97	0.66
13	North Slope	Slope	0	96	O- L. telekii/ D. keniodendron	0	27	4000	34.60	200.84	0.71	1.91	0.01	0.58
14	South Slope	Slope	0	100	O- L. telekii/ D. keniodendron	0	26	4111	34.65	348.51	0.90	0.63	1.00	0.50
15	Riverside	Valley Bottom	1.5	95.5	K- D. keniensis/ L. keniensis	150	1	4090	28.08	339.99	0.67	0.50	1.00	0.50
16	North Ridge	Ridge	54.7	45.3	O- L. telekii/ D. keniodendron	0	13	4240	39.05	186.16	0.43	1.77	0.02	0.35
17	South Ridge	Ridge	14.3	83.2	O- L. telekii/ D. keniodendron	0	18	4223	20.36	351.98	0.71	1.42	1.00	0.46
18	North Valley Bottom	Valley Bottom	0	95	K- D. keniensis/ L. keniensis	150	0	4090	28.08	339.99	0.67	0.00	0.00	0.46
19	South Valley Bottom	Valley Bottom	1	89	K- D. keniensis/ L. keniensis	100	7	4131	42.35	347.83	0.85	1.00	1.00	0.51
20	North Slope	Slope	0	92	O- L. telekii/ D. keniodendron	0	3	4109	31.66	194.10	0.72	2.17	0.00	0.50
21	South Slope	Slope	0	98.5	P- Festuca pilgeri/ Alchemilla argyrophylla	0	0	4165	37.32	339.86	0.75	0.00	1.00	0.50
22	Riverside	Valley Bottom	0.5	96.5	N- Carex-Bog	6	62	4152	21.82	342.69	0.76	0.52	0.50	0.00
23	North Ridge	Ridge	52.5	47.5	P- Festuca pilgeri/ Alchemilla argyrophylla	0	7	4315	39.15	187.35	N/A	1.21	0.02	0.63
24	South Ridge	Ridge	84.6	15.4	R- Open L. telekii	0	6	4378	20.56	210.45	0.23	1.00	0.99	0.59
25	North Valley Bottom	Valley Bottom	4	92	N- Carex-Bog	0	52	4146	20.46	343.48	0.73	0.50	0.01	0.59
26	South Valley Bottom	Valley Bottom	0	98	K- D. keniensis/ L. keniensis	3	32	4179	42.19	348.91	0.80	0.75	1.00	0.57
27	North Slope	Slope	26	71	O- L. telekii/ D. keniodendron	0	19	4176	44.62	184.00	0.53	1.45	0.05	0.71
28	South Slope	Slope	4	93	P- Festuca pilgeri/ Alchemilla argyrophylla	0	22	4273	66.55	349.70	0.29	0.57	1.00	0.50
29	Riverside	Valley Bottom	2	98	N- Carex-Bog	6	6	4170	20.47	352.41	0.74	0.50	0.50	0.00
30	North Ridge	Ridge	96.2	3.8	P- Festuca pilgeri/ Alchemilla argyrophylla	0	0	4461	31.58	173.61	N/A	0.00	0.18	0.88
31	South Ridge	Ridge	99.2	0.8	S- Senecio keniophytum	0	3	4511	16.76	206.36	N/A	1.00	1.00	0.51
32	North Valley Bottom	Valley Bottom	1	96.5	M- D. keniensis/ D. keniodendron	130	7	4164	1.88	291.04	0.75	0.50	0.01	0.59
33	South Valley Bottom	Valley Bottom	0	100	M- D. keniensis/ D. keniodendron	0	16	4201	41.22	356.24	0.71	0.53	0.99	0.59
34	North Slope	Slope	59.5	37.5	O- L. telekii/ D. keniodendron	0	9	4275	43.97	180.53	0.16	1.00	0.07	0.75
35	South Slope	Slope	62.5	35.5	P- Festuca pilgeri/ Alchemilla argyrophylla	0	4	4413	63.55	355.11	0.66	1.50	1.00	0.57

D4- Questionnaire respondents

ID	Age	Sex	Ethnicity	Education	Resident?	Local?	Occupation	Changes Observed
1	28	Male	Other	Primary School	Yes	Yes	Day / Unskilled laborer	Species Range Changes
2	36	Male	Kalenjin	Secondary School	Yes	No	Day / Unskilled laborer	Species Range Changes
3	52	Male	Kalenjin	Primary School	Yes	No	Business owner	Species Composition Changes
4	49	Male	Luhya	Secondary School	Yes	No	Professional	Species Range Changes Other Species Composition Changes Soil Fertility Changes
5	41	Male	Luhya	Secondary School	Yes	No	Day / Unskilled laborer	Other Soil Fertility Changes Species Range Changes
6	22	Male	Kikuyu	Secondary School	Yes	Yes	Day / Unskilled laborer	Rainfall Pattern Changes Temperature Changes
7	22	Male	Kikuyu	Secondary School	Yes	No	Other	Species Range Changes
8	72	Male	Kikuyu	Primary School	Yes	Yes	Government employee	None
9	46	Male	Kalenjin	Secondary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes Changes in streamflow Species Composition Changes
10	20	Male	Kalenjin	Primary School	No	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes
11	24	Male	Kalenjin	Primary School	Yes	Yes	Farmer / Agriculturalist	None
12	29	Male	Kalenjin	Secondary School	Yes	No	Farmer / Agriculturalist	Rainfall Pattern Changes Temperature Changes Species Range Changes
13	60	Female	Luhya	Primary School	No	Yes	Farmer / Agriculturalist	Soil Fertility Changes
14	36	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Changes in streamflow Rainfall Pattern Changes Soil Fertility Changes Species Composition Changes
15	71	Male	Kalenjin	Secondary School	Yes	No	Farmer / Agriculturalist	Rainfall Pattern Changes Changes in streamflow
16	38	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Rainfall Pattern Changes Soil Fertility Changes Species Composition Changes
17	35	Female	Kalenjin	Diploma	Yes	Yes	Business owner	Rainfall Pattern Changes
18	50	Male	Kalenjin	Primary School	Yes	No	Other	Soil Fertility Changes Species Composition Changes
19	42	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Species Range Changes Changes in streamflow Soil Fertility Changes Rainfall Pattern Changes
20	61	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Temperature Changes Species Range Changes Changes in streamflow
21	32	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	None
22	48	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	None
23	25	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Rainfall Pattern Changes Changes in streamflow
24	59	Male	Kalenjin	Diploma	Yes	No	Professional	Species Range Changes Rainfall Pattern Changes Temperature Changes Species Composition Changes
25	49	Male	Kalenjin	Secondary School	Yes	No	Farmer / Agriculturalist	Species Composition Changes Species Range Changes
26	37	Male	Kalenjin	Primary School	Yes	No	Day / Unskilled laborer	Temperature Changes Rainfall Pattern Changes
27	30	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Species Composition Changes Species Range Changes Soil Fertility Changes Changes in streamflow
28	58	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Species Composition Changes
29	58	Female	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Species Composition Changes Changes in water quality
30	35	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Species Range Changes Species Composition Changes Rainfall Pattern Changes Soil Fertility Changes
31	43	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Temperature Changes Rainfall Pattern Changes Changes in streamflow
32	21	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	None
33	65	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Species Range Changes Species Composition Changes
34	70	Female	Kalenjin	Secondary School	Yes	Yes	Farmer / Agriculturalist	Species Composition Changes Rainfall Pattern Changes Other Temperature Changes
35	60	Male	Kalenjin	Primary School	Yes	Yes	Farmer / Agriculturalist	Other Soil Fertility Changes
36	28	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Temperature Changes Soil Fertility Changes
37	50	Male	Kalenjin	Primary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes Temperature Changes
38	58	Male	Kalenjin	Primary School	No	Yes	Farmer / Agriculturalist	Temperature Changes Species Range Changes Changes in water quality Rainfall Pattern Changes Soil Fertility Changes
39	20	Male	Kalenjin	Secondary School	Yes	No	Farmer / Agriculturalist	Species Composition Changes Temperature Changes Soil Fertility Changes

40	58	Female	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Rainfall Pattern Changes Temperature Changes Soil Fertility Changes
41	23	Female	Kalenjin	Secondary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes Species Composition Changes Temperature Changes
42	26	Male	Kalenjin	Secondary School	Yes	No	Farmer / Agriculturalist	Temperature Changes Soil Fertility Changes Rainfall Pattern Changes
43	28	Male	Kalenjin	Primary School	Yes	No	Business owner	Temperature Changes Species Range Changes Changes in water quality Soil Fertility Changes Rainfall Pattern Changes
44	34	Male	Kalenjin	Secondary School	Yes	Yes	Farmer / Agriculturalist	Temperature Changes Soil Fertility Changes Rainfall Pattern Changes
45	44	Male	Kalenjin	Primary School	Yes	Yes	Farmer / Agriculturalist	Temperature Changes Changes in water quality Soil Fertility Changes Rainfall Pattern Changes Species Composition Changes
46	32	Female	Kalenjin	Secondary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes Temperature Changes Soil Fertility Changes
47	53	Male	Kalenjin	Primary School	Yes	Yes	Farmer / Agriculturalist	Temperature Changes Soil Fertility Changes Rainfall Pattern Changes
48	47	Female	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Temperature Changes Changes in water quality Soil Fertility Changes Rainfall Pattern Changes
49	60	Male	Kikuyu	Primary School	Yes	Yes	Other	Temperature Changes Rainfall Pattern Changes Soil Fertility Changes
50	28	Male	Luhya	Primary School	Yes	Yes	Farmer / Agriculturalist	Temperature Changes Rainfall Pattern Changes
51	30	Male	Kalenjin	Primary School	Yes	No	Business owner	Temperature Changes Rainfall Pattern Changes
52	27	Male	Kalenjin	Secondary School	Yes	No	Farmer / Agriculturalist	None
53	67	Male	Kalenjin	Secondary School	Yes	No	Farmer / Agriculturalist	Rainfall Pattern Changes
54	18	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Temperature Changes Changes in streamflow Rainfall Pattern Changes
55	50	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Rainfall Pattern Changes Species Range Changes Soil Fertility Changes Temperature Changes
56	57	Female	Maasai	Primary School	Yes	No	Farmer / Agriculturalist	Rainfall Pattern Changes Temperature Changes Changes in water quality Species Range Changes Species Composition Changes Soil Fertility Changes
57	48	Male	Kalenjin	Secondary School	Yes	No	Farmer / Agriculturalist	Species Range Changes Species Composition Changes Changes in water quality Temperature Changes Rainfall Pattern Changes
58	49	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Other Species Range Changes
59	34	Male	Luhya	Secondary School	Yes	No	Day / Unskilled laborer	Rainfall Pattern Changes Temperature Changes
60	80	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Species Composition Changes Changes in streamflow Temperature Changes Rainfall Pattern Changes
61	27	Male	Luhya	Primary School	Yes	No	Farmer / Agriculturalist	Rainfall Pattern Changes Temperature Changes Soil Fertility Changes
62	60	Female	Luhya	Primary School	Yes	No	Farmer / Agriculturalist	Other Soil Fertility Changes Rainfall Pattern Changes Temperature Changes Species Range Changes
63	61	Male	Kalenjin	Secondary School	Yes	No	Farmer / Agriculturalist	Other Temperature Changes Soil Fertility Changes
64	22	Female	Kalenjin	Secondary School	Yes	No	Other	Soil Fertility Changes Changes in streamflow Species Composition Changes Temperature Changes
65	46	Female	Kalenjin	Diploma	Yes	No	Professional	Species Range Changes Rainfall Pattern Changes
66	30	Female	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Rainfall Pattern Changes Temperature Changes Soil Fertility Changes
67	15	Male	Kalenjin	Secondary School	Yes	No	Other	Rainfall Pattern Changes Soil Fertility Changes Temperature Changes
68	17	Male	Kalenjin	Secondary School	Yes	No	Other	Rainfall Pattern Changes Soil Fertility Changes
69	21	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Soil Fertility Changes Rainfall Pattern Changes
70	24	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Rainfall Pattern Changes Soil Fertility Changes
71	50	Male	Kalenjin	Secondary School	Yes	No	Farmer / Agriculturalist	Rainfall Pattern Changes
72	30	Female	Luhya	Primary School	Yes	No	Farmer / Agriculturalist	None
73	39	Female	Kalenjin	Primary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes
74	35	Female	Kalenjin	Secondary School	Yes	No	Farmer / Agriculturalist	Species Composition Changes Rainfall Pattern Changes Soil Fertility Changes
75	38	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	None
76	53	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	None
77	52	Male	Kalenjin	Secondary School	Yes	No	Farmer / Agriculturalist	None
78	51	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Rainfall Pattern Changes Changes in water quality Species Range Changes
79	70	Male	Luhya	Primary School	Yes	No	Farmer / Agriculturalist	Soil Fertility Changes Rainfall Pattern Changes
80	25	Male	Kalenjin	Secondary School	Yes	No	Business owner	Rainfall Pattern Changes Changes in streamflow

81	58	Male	Kalenjin	Secondary School	Yes	No	Farmer / Agriculturalist	Species Composition Changes Soil Fertility Changes Rainfall Pattern Changes
82	27	Male	Kalenjin	Secondary School	Yes	No	Day / Unskilled laborer	Species Range Changes Rainfall Pattern Changes Changes in streamflow Temperature Changes
83	47	Male	Luhya	Secondary School	Yes	No	Farmer / Agriculturalist	None
84	35	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	None
85	63	Male	Kalenjin	Secondary School	Yes	No	Professional	Species Range Changes Soil Fertility Changes
86	43	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Species Range Changes Changes in streamflow Soil Fertility Changes
87	42	Female	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Temperature Changes
88	68	Female	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Species Range Changes Changes in streamflow
89	22	Male	Luhya	Secondary School	Yes	No	Farmer / Agriculturalist	None
90	76	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	None
91	19	Male	Kalenjin	Secondary School	Yes	No	Other	None
92	30	Female	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Soil Fertility Changes Temperature Changes Rainfall Pattern Changes
93	50	Female	Kalenjin	Primary School	Yes	Yes	Farmer / Agriculturalist	None
94	45	Female	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	None
95	36	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	None
96	44	Male	Luhya	Primary School	Yes	No	Farmer / Agriculturalist	None
97	23	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	None
98	37	Male	Kalenjin	Primary School	Yes	No	Farmer / Agriculturalist	Temperature Changes Rainfall Pattern Changes Soil Fertility Changes
99	22	Female	Kalenjin	Primary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes
100	32	Male	Kikuyu	Diploma	Yes	No	Other	Rainfall Pattern Changes
101	43	Male	Kikuyu	Primary School	Yes	Yes	Business owner	Changes in water quality Changes in streamflow Rainfall Pattern Changes
102	26	Male	Kikuyu	Secondary School	Yes	No	Other	Changes in water quality Soil Fertility Changes Rainfall Pattern Changes Temperature Changes
103	64	Male	Meru	Primary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes Species Composition Changes
104	39	Male	Kikuyu	Primary School	Yes	Yes	Business owner	Rainfall Pattern Changes Changes in water quality Temperature Changes Changes in streamflow Species Composition Changes
105	40	Male	Kikuyu	Secondary School	Yes	No	Farmer / Agriculturalist	Temperature Changes Rainfall Pattern Changes
106	35	Male	Meru	Secondary School	No	Yes	Other	Soil Fertility Changes Rainfall Pattern Changes Temperature Changes
107	54	Male	Kikuyu	Primary School	Yes	Yes	Farmer / Agriculturalist	None
108	75	Male	Kikuyu	Primary School	Yes	Yes	Farmer / Agriculturalist	Temperature Changes Species Composition Changes Changes in water quality Soil Fertility Changes Rainfall Pattern Changes
109	43	Male	Meru	Secondary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes Temperature Changes Changes in streamflow
110	55	Male	Kikuyu	Secondary School	Yes	No	Farmer / Agriculturalist	Temperature Changes Species Range Changes Other Changes in streamflow Rainfall Pattern Changes
111	24	Male	Kikuyu	Secondary School	Yes	No	Farmer / Agriculturalist	Species Range Changes Species Composition Changes Rainfall Pattern Changes
112	42	Male	Kikuyu	Secondary School	Yes	No	Day / Unskilled laborer	Rainfall Pattern Changes Temperature Changes
113	23	Male	Kikuyu	Secondary School	Yes	Yes	Business owner	Rainfall Pattern Changes Temperature Changes Changes in streamflow
114	35	Male	Kikuyu	Primary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes
115	26	Male	Kikuyu	Secondary School	Yes	No	Farmer / Agriculturalist	Other Temperature Changes Changes in streamflow Rainfall Pattern Changes
116	48	Male	Kikuyu	Secondary School	Yes	Yes	Business owner	Rainfall Pattern Changes Species Range Changes Temperature Changes Changes in streamflow
117	56	Male	Kikuyu	Diploma	Yes	No	Day / Unskilled laborer	Species Range Changes Rainfall Pattern Changes
118	22	Female	Kikuyu	Secondary School	Yes	No	Business owner	Rainfall Pattern Changes
119	32	Male	Kikuyu	Secondary School	Yes	No	Farmer / Agriculturalist	Changes in water quality Rainfall Pattern Changes Soil Fertility Changes Temperature Changes
120	21	Male	Kikuyu	Secondary School	Yes	No	Farmer / Agriculturalist	Temperature Changes Changes in streamflow Changes in water quality Rainfall Pattern Changes
121	42	Male	Kikuyu	Secondary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes Soil Fertility Changes
122	24	Male	Kikuyu	Primary School	Yes	No	Farmer / Agriculturalist	None

123	42	Male	Meru	Primary School	Yes	Yes	Business owner	None
124	21	Male	Kikuyu	Secondary School	Yes	Yes	Professional	None
125	24	Male	Kikuyu	Secondary School	Yes	No	Professional	Species Composition Changes Species Range Changes Rainfall Pattern Changes
126	50	Male	Kikuyu	Secondary School	Yes	No	Business owner	Rainfall Pattern Changes Soil Fertility Changes Changes in streamflow
127	51	Male	Meru	Primary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes
128	38	Male	Meru	Primary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes
129	45	Male	Kikuyu	Secondary School	Yes	No	Other	Temperature Changes Species Range Changes Rainfall Pattern Changes
130	36	Female	Kikuyu	Secondary School	Yes	Yes	Business owner	Rainfall Pattern Changes Temperature Changes Changes in streamflow
131	53	Male	Kikuyu	Primary School	Yes	No	Professional	Rainfall Pattern Changes Changes in streamflow
132	58	Male	Kikuyu	Primary School	Yes	No	Day / Unskilled laborer	None
133	50	Male	Kikuyu	Diploma	Yes	No	Day / Unskilled laborer	None
134	53	Female	Luhya	Diploma	Yes	No	Professional	Species Range Changes Rainfall Pattern Changes Changes in streamflow
135	37	Male	Kikuyu	Diploma	Yes	No	Other	Temperature Changes Rainfall Pattern Changes Changes in streamflow
136	62	Male	Kikuyu	Secondary School	Yes	No	Day / Unskilled laborer	Rainfall Pattern Changes Changes in streamflow Temperature Changes Species Range Changes Soil Fertility Changes
137	38	Male	Kikuyu	Secondary School	Yes	No	Business owner	Changes in streamflow Species Range Changes Rainfall Pattern Changes
138	23	Male	Kikuyu	Secondary School	Yes	No	Day / Unskilled laborer	Rainfall Pattern Changes
139	45	Male	Kikuyu	Secondary School	Yes	Yes	Business owner	Rainfall Pattern Changes Temperature Changes Changes in streamflow
140	50	Male	Kikuyu	Primary School	Yes	No	Day / Unskilled laborer	Temperature Changes Soil Fertility Changes Rainfall Pattern Changes Changes in streamflow
141	43	Female	Meru	Secondary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes Changes in streamflow
142	23	Female	Kikuyu	Diploma	Yes	No	Other	Rainfall Pattern Changes Changes in streamflow
143	25	Male	Kikuyu	Secondary School	Yes	No	Day / Unskilled laborer	Temperature Changes Rainfall Pattern Changes
144	25	Male	Kikuyu	Primary School	Yes	No	Business owner	None
145	82	Male	Kikuyu	Primary School	Yes	Yes	Farmer / Agriculturalist	Soil Fertility Changes Temperature Changes Rainfall Pattern Changes
146	21	Female	Meru	Diploma	Yes	No	Other	Rainfall Pattern Changes Changes in water quality Temperature Changes
147	24	Male	Kikuyu	Secondary School	Yes	No	Day / Unskilled laborer	Rainfall Pattern Changes Temperature Changes
148	23	Male	Kikuyu	Diploma	Yes	No	Business owner	Rainfall Pattern Changes
149	34	Female	Kikuyu	Secondary School	Yes	Yes	Business owner	Rainfall Pattern Changes
150	26	Male	Kikuyu	Secondary School	Yes	Yes	Other	Species Range Changes Changes in water quality Rainfall Pattern Changes Species Composition Changes
151	24	Male	Kikuyu	Secondary School	Yes	Yes	Day / Unskilled laborer	Temperature Changes Soil Fertility Changes Rainfall Pattern Changes
152	22	Male	Kikuyu	Secondary School	Yes	No	Other	Rainfall Pattern Changes Changes in streamflow Temperature Changes
153	23	Male	Kikuyu	Diploma	No	Yes	Other	None
154	18	Male	Kikuyu	Secondary School	Yes	No	Other	Rainfall Pattern Changes Temperature Changes
155	21	Male	Kikuyu	Secondary School	Yes	No	Other	None
156	42	Male	Kikuyu	Primary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes
157	36	Male	Kikuyu	Primary School	Yes	No	Day / Unskilled laborer	Rainfall Pattern Changes Species Range Changes
158	45	Male	Meru	Primary School	Yes	Yes	Other	Rainfall Pattern Changes
159	68	Male	Kikuyu	Secondary School	Yes	Yes	Farmer / Agriculturalist	None
160	22	Female	Kikuyu	Secondary School	Yes	No	Other	Rainfall Pattern Changes Temperature Changes
161	43	Male	Kikuyu	Primary School	Yes	Yes	Professional	None
162	56	Male	Kikuyu	Primary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes Temperature Changes
163	32	Male	Meru	Primary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes Soil Fertility Changes
164	35	Male	Meru	Primary School	Yes	Yes	Farmer / Agriculturalist	Temperature Changes Rainfall Pattern Changes
165	43	Female	Kikuyu	Secondary School	Yes	Yes	Business owner	Temperature Changes Soil Fertility Changes Rainfall Pattern Changes
166	29	Female	Kikuyu	Diploma	Yes	Yes	Government employee	Temperature Changes Species Composition Changes Rainfall Pattern Changes Soil Fertility Changes
167	59	Male	Kikuyu	Primary School	Yes	Yes	Farmer / Agriculturalist	Temperature Changes Rainfall Pattern Changes

168	52	Female	Kikuyu	Primary School	Yes	No	Farmer / Agriculturalist	None
169	45	Male	Kikuyu	Primary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes Temperature Changes
170	23	Male	Kikuyu	Secondary School	Yes	Yes	Business owner	Temperature Changes Soil Fertility Changes Rainfall Pattern Changes
171	41	Male	Meru	Primary School	Yes	Yes	Farmer / Agriculturalist	Soil Fertility Changes Rainfall Pattern Changes
172	48	Female	Kikuyu	Primary School	Yes	Yes	Business owner	Rainfall Pattern Changes Soil Fertility Changes
173	69	Male	Kikuyu	Primary School	Yes	No	Farmer / Agriculturalist	Soil Fertility Changes Rainfall Pattern Changes
174	68	Male	Kikuyu	Primary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes Soil Fertility Changes
175	45	Male	Meru	Secondary School	Yes	Yes	Business owner	None
176	49	Male	Kikuyu	Diploma	Yes	No	Business owner	Temperature Changes Species Range Changes Changes in streamflow Rainfall Pattern Changes Soil Fertility Changes
177	41	Male	Meru	Primary School	Yes	Yes	Farmer / Agriculturalist	None
178	38	Male	Meru	Primary School	Yes	Yes	Farmer / Agriculturalist	Species Range Changes Soil Fertility Changes Rainfall Pattern Changes
179	50	Male	Meru	Primary School	Yes	Yes	Farmer / Agriculturalist	None
180	24	Female	Meru	Diploma	Yes	Yes	Business owner	Rainfall Pattern Changes
181	27	Female	Kikuyu	Diploma	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes
182	14	Female	Kalenjin	Primary School	No	No	Other	None
183	46	Female	Kikuyu	Secondary School	Yes	Yes	Farmer / Agriculturalist	None
184	22	Male	Kikuyu	University Degree	Yes	No	Professional	Rainfall Pattern Changes Species Range Changes Temperature Changes
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186	40	Male	Kikuyu	Diploma	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes
187	45	Male	Kikuyu	Primary School	Yes	No	Farmer / Agriculturalist	Rainfall Pattern Changes Temperature Changes
188	59	Male	Kikuyu	Primary School	Yes	Yes	Business owner	Rainfall Pattern Changes
189	24	Male	Kikuyu	Secondary School	Yes	Yes	Farmer / Agriculturalist	Soil Fertility Changes Rainfall Pattern Changes Temperature Changes
190	30	Male	Kikuyu	Primary School	Yes	No	Farmer / Agriculturalist	Rainfall Pattern Changes Soil Fertility Changes Temperature Changes
191	58	Male	Kikuyu	Secondary School	Yes	No	Farmer / Agriculturalist	Soil Fertility Changes Rainfall Pattern Changes
192	19	Male	Kikuyu	Secondary School	Yes	No	Farmer / Agriculturalist	Temperature Changes Soil Fertility Changes Rainfall Pattern Changes
193	34	Male	Kikuyu	Secondary School	Yes	Yes	Other	None
194	37	Male	Kikuyu	Primary School	Yes	Yes	Farmer / Agriculturalist	None
195	23	Male	Kikuyu	Secondary School	Yes	Yes	Business owner	Temperature Changes Rainfall Pattern Changes
196	22	Male	Kikuyu	University Degree	Yes	No	Business owner	Rainfall Pattern Changes
197	68	Male	Kikuyu	Primary School	Yes	Yes	Farmer / Agriculturalist	Temperature Changes Soil Fertility Changes Rainfall Pattern Changes
198	63	Male	Kikuyu	Primary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes Temperature Changes Species Composition Changes Changes in streamflow Changes in water quality
199	63	Male	Kikuyu	Primary School	Yes	Yes	Business owner	Soil Fertility Changes Rainfall Pattern Changes
200	55	Male	Kikuyu	Primary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes
201	36	Female	Kikuyu	Secondary School	Yes	Yes	Business owner	Rainfall Pattern Changes Soil Fertility Changes
202	54	Male	Kikuyu	Primary School	Yes	Yes	Farmer / Agriculturalist	Rainfall Pattern Changes Temperature Changes Soil Fertility Changes
203	48	Male	Kikuyu	Secondary School	Yes	Yes	Business owner	Temperature Changes Changes in water quality Rainfall Pattern Changes
204	60	Female	Kikuyu	Primary School	Yes	Yes	Business owner	Temperature Changes Soil Fertility Changes Rainfall Pattern Changes
205	38	Female	Kikuyu	Diploma	Yes	Yes	Business owner	Rainfall Pattern Changes Temperature Changes Soil Fertility Changes
206	21	Female	Kikuyu	Secondary School	Yes	No	Business owner	Temperature Changes Soil Fertility Changes Rainfall Pattern Changes
207	23	Female	Kikuyu	Diploma	Yes	No	Business owner	None
208	41	Female	Kikuyu	Secondary School	Yes	Yes	Business owner	Temperature Changes Rainfall Pattern Changes Soil Fertility Changes
209	23	Female	Kikuyu	Diploma	Yes	No	Other	Rainfall Pattern Changes Changes in streamflow

APPENDIX E: Policy Brief

Impacts of climate change in the alpine regions of Kenya

Written by Timothy A. Downing, University of Nairobi

Executive summary

Climate change has impacted the socio-ecological systems surrounding the alpine areas of Kenya. Temperatures have increased in the alpine zone and precipitation patterns have been altered at the base of the mountains, which has begun to affect local livelihoods. However, there is also resilience in the system: vegetation communities in the alpine zone have not experienced much change over the last 50 years, and local communities still do not feel climate change to be an existential threat. Nonetheless there are indications of thresholds and tipping points, suggesting that this resilience may be tested in the future.

Key messages and recommendations

- The alpine regions of Kenya are unique and important ecosystems that provide vital ecosystem services to the country
- Climate change is impacting these important ecosystems in ways that are still not fully understood, and this will have impacts on downstream communities that rely on mountain services
- The alpine region has already warmed by at least 2°C over the last half century which is faster than the average warming across the globe
- Despite this higher level of warming, the ecosystem so far has changed less than expected, suggesting an underlying inertia or resilience
- There are indications that there could be tipping points beyond which major irreversible changes are likely
- Downstream communities have so far been somewhat buffered from the changes that have occurred, and express optimism about their ability to handle changes in the future
- More monitoring and research are needed in these vital ecosystems to better understand climate impacts

Introduction/Problem/Context

Tropical alpine environments are complex ecological systems that have evolved under the very tight envelope of conditions that exist in an equatorial mountain. These ecosystem are thus both rare and fragile. The plant communities that have evolved are phenotypically similar in all tropical alpine areas of the world, despite vast geographic separation. The tropical alpine areas of East Africa (the Afro-alpine system) are particularly fragile because they are not part of a mountain range, so each summit acts as an island. As the climate warms, the alpine zone will be forced to move upwards in elevation causing these afro-alpine islands to shrink. Tropical alpine areas are also predicted to experience absolute higher level of warming than other areas of the globe. The combination of high exposure to warming as well as potential sensitivity to that warming, make afro-alpine areas particularly vulnerable to climate change. Like the Artic, they are at the forefront of climate; unlike the Artic, they are less insulated from the rest of the world, as millions of people directly rely on these mountains for their survival. It is thus important to know how climate change will affect these areas and how it will impact the livelihoods of the millions relying on these ecosystem services.

About the study/project

Afro alpine system can be thought of as a tight socio-ecological landscape, where climate, ecology, culture, and society are all inter-linked. Climate change therefore can have profound impacts throughout this system, depending on the vulnerability or resilience of each component of the system. The aim of the project was to analyse the trends and pattern in the afro-alpine ecosystem of Kenya in order to assess its vulnerability to climate change. Vulnerability is a function of exposure and sensitivity. Biophysically, this is the extent to which an ecosystem is exposed to changing weather patterns and are affected by them. Socio-economically, it is the extent to which a society relies on their surrounding environment and is affected by changes in that environment. Climate trends were analysed using satellite-derived reanalysis datasets, vegetation trends were explored through a resurvey of a historic vegetation study on Mount Kenya, and societal trends were assessed using qualitative and quantitative socio-economic methods.

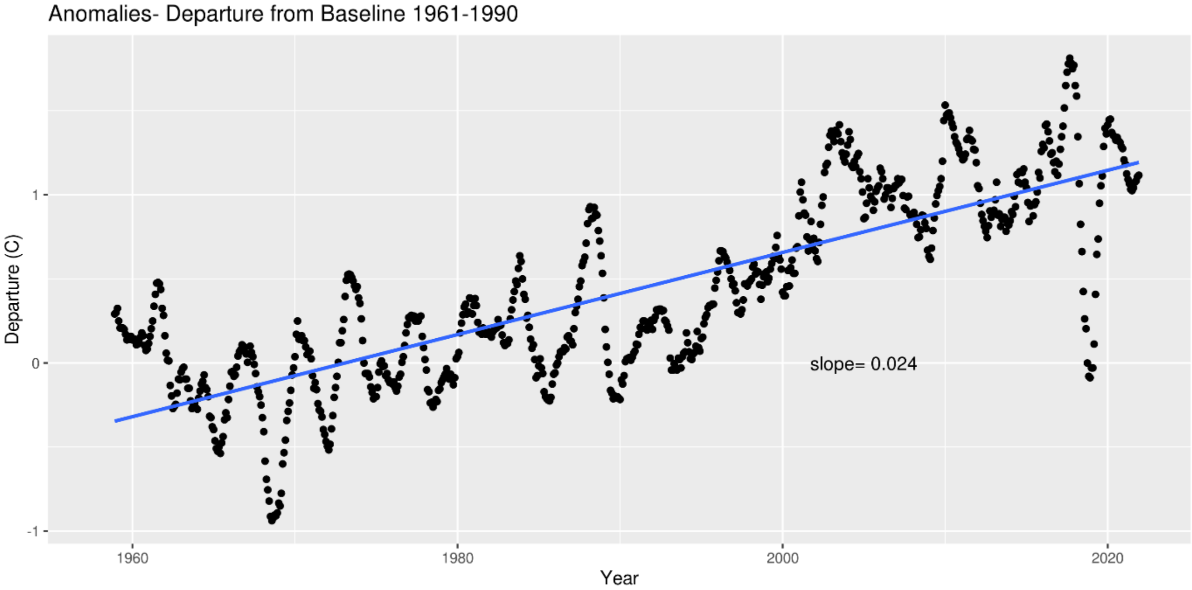
> *“You can see the importance of the mountain to the local people- indigenous people- and their belief was that...God does not reside on mountains, he is all over, but mountains are his store. If it is not his dwelling house- not his state-house- then it is his store. Because this is where you get supplies- water for life.”*
>
> *[Mount Kenya Interviewee, September, 2021]*

Study results

Temperature is increasing

Temperature has warmed consistently over the past 60 years in the alpine regions of Kenya. In both Mount Elgon and Mount Kenya satellite derived data suggests warming of around 2° C over the past half century. At the Naro Moru Meterological Station (3050m), the satellite data since 1958 shows warming of 0.24 C/ decade when graphed as departures from the baseline data of 1960-1990.

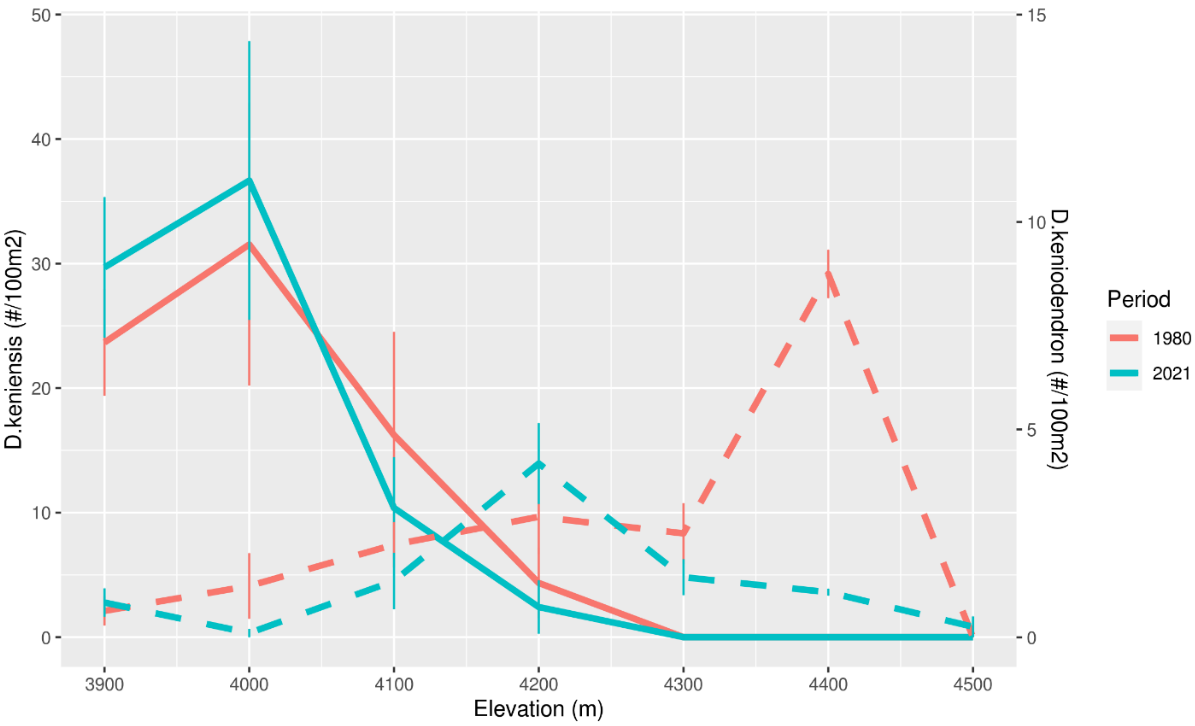
Dendrosenecio keniodendron in Teleki Valley, Mount Kenya, © Timothy Downing 2021



Warming on Mount Kenya: *Temperature trend at Met Station on Mount Kenya from TerraClimate reanalysis data. Data is displayed as departures from the baseline temperature from 1960-1990*

There is inertia in the alpine plant communities

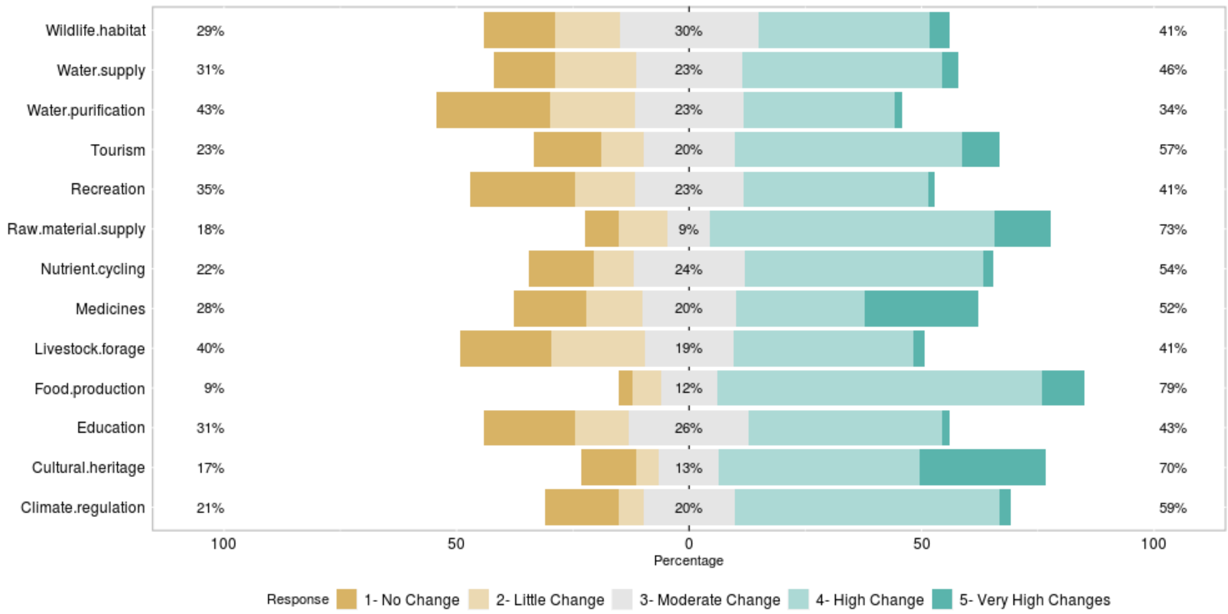
Despites this warming, plant communities have largely been unchanged over the last 40 years in the Teleki Valley of Mount Kenya. The dominant alpine species have similar distributions today as they did in 1980. Looking in particular the most prominent genus of the alpine zone, the *Dendrosenecios*, densities are comparable by elevation as they were in 1980. The main difference is a decline in abundance of *Dendrosencio keniodendron* in the higher elevations in 2021.



__Giant Senecio densities in Teleki Valley:__ Changes in densities by elevation of the two dominant species in Teleki Valley: Dendrosenecio keniodendron and Dendrosenecion keniensis from 1980 to 2021.

Ecosystem services have changed

Local communities have documented changes in the ecosystem services provided by the mountain. The majority have seen high or very high changes in ecosystem service delivery over their lifetimes. The changes seen were mostly declines in service delivery. Provisioning services (raw materials and food provision) were seen to have changed the most by the majority of respondents, while cultural services (cultural heritage and medicines) attracted the strongest feelings of change (most 'very high change' responses).



__Community perceptions on change:__ Perceived level of change for ecosystem services. Bars are centred on the neutral response (moderate change) - stronger feelings are indicated in blue (and summarized as a percentage), weaker feelings are indicated in brown (indicated as a percentage).

Climate changes are consistent with IPCC report predictions

The changes documented in this study and local observations are consistent with Intergovernmental Panel on Climate Change (IPCC). Differences are mostly seen in vegetation trends, which have not changed yet to the extent predicted by the IPCC. Increases in temperature and changes in weather patterns are seen in this study and in local observations, and these confirm model predictions. Vegetation changes are more cryptic, however, with the current study and local observations suggesting both upward and downward movements, rather than the unidirectional shifts predicted by the climate models.

Comparison of observed changes with model predictions: *Table comparing observed changes with predictions for high mountain areas in the IPCC special report on Oceans and Cryosphere (IPCC, 2022)*

Parameter	Current Study	Local Observations	IPCC Predictions
Climate	Monotonic increase in mean and minimum temperatures (according to reanalysis data and in-situ loggers). No change in precipitation on the mountain, but changes in seasonality at the base	Warming temperatures in the day, but colder temperatures at night. Loss of ice and snow on the mountain. Decline in precipitation; changing rainfall patterns and increasing unpredictability	Increases in mean temperatures; ice melting and permafrost thawing. Changes in runoff patterns on the mountain leading to increasing variability in streamflow and long-term declines in baseflow
Vegetation	Few significant changes in plant distribution, but suggestions of both upward and downward movements; uggestions of species disappearances and mortality of older Senecios	Plants moving both up wards and downwards in elevation; mortality of Senecios and appearance of new plants; faster growth of plants at higher elevations	Upslope movements of species leading to increasing diversity in the alpine zone, but also extinction of certain cold-adapted species
Ecosystem Services	Changes (mostly negative) in almost all ecosystem services- provisioning, regulating, and cultural. Largest changes in provisioning and cultural services		Large changes in cultural services, particularly tourism and recreation

Local communities are concerned but optimistic

Local communities expressed concern about the impacts of climate change, noting that weather patterns had changed and were increasingly unpredictable which had affected their daily livelihood. Nonetheless when asked to list the primary challenge facing their lives, few listed climate change or environmental concerns as a primary concern, rather listing employment, food prices or political challenges. Many expressed optimism about their ability to adapt to future challenges.

> *“The global change- this community is positive. They are able to adapt to any incoming issues, any challenges that have come. And any issue that will enable the... the challenges will change from negative to positive- they are ready. Our community are ready, and some have started- some have started planting trees..”*
>
> *[Mount Elgon Interviewee, September, 2021]*

Conclusions and recommendations

This study has shown that changes have occurred and are occurring in this fragile landscape. Temperature has increased appreciably on the mountain, increasing by over 2° C over the last half century. On the lower elevations, precipitation patterns have been altered and so has discharge patterns: baseflow has declined while at the same time variability has increased. These changes are in line with model predictions and also with local observations of change. The biophysical sensitivity to these changes have been more nuanced. Dominant vegetation patterns have not changed much, though there is evidence of some plant shifting. The magnitude of these changes is rather small, however, suggesting a resilience in the ecological system. Nonetheless, there is suggestion of species declines and changes in plant community makeup which could indicate longer term changes. This inertia in the vegetation is somewhat at odds with the model results, although given the slow life-history of the plant communities on the mountain, it is probably not surprising for this relatively short time frame. Human communities were found to be very reliant on mountain resources, and had witnessed declines in most mountain ecosystem services over their lifetimes. Here again, however, there were suggestions of resilience, as the communities displayed a high degree optimism regarding climate change, and few listed it as their number one concern.

RECOMMENDATIONS

Enhance the long-term climate monitoring networks in the alpine areas of Kenya. This includes increasing the density of meteorological stations to account for the complex topography, collecting data on more parameters, increasing the temporal resolution of the data, and conducting routine maintenance and calibration of sensors. Furthermore, this could involve making use of mountain guides to make regular observations and document changes; this is a largely untapped network of 'citizen scientists' who are consistent visitors to these remote areas.

Foster ecological research in the alpine areas of Kenya. More research is needed to understand ecological processes and their specific vulnerabilities. Using a programme like GLORIA (Global Observation Research Initiative in Alpine Environments) is recommended as it ensures consistency in the studies and allows for comparisons with other mountain areas around the world. In addition, the conducting of research in these ecosystems should be facilitated; this involves removing roadblocks to conducting research, making data easily accessible, streamlining the permitting process, and improving information sharing among agencies and universities.

Increase awareness and education of these important ecosystems. This can start at the primary school level and continue through University. People should be encouraged to visit and study Kenya's mountains enhance appreciation and respect for these valuable landscape.

Support local conservation initiatives. The local users associations have many great ideas for conservation, but they are chronically underfunded and lack the capability to undertake large

Enforce existing regulations of the National Parks and Forests.

Upper Teleki Valley, Mount Kenya, © Timothy Downing 2022

Limitations

This is an exploratory study and is therefore limited in scope. It is spatially and temporally limited and so can only provide provisional results that hopefully can encourage future researchers to engage in longer-term, in-depth studies, over larger geographic areas.

Acknowledgements

We acknowledge colleagues at the University of Nairobi for valuable insight, the Kenya Wildlife Service and county governments for facilitating the research, and our field assistants (Dennis Nabie and William Murigu) who assisted in the data collection and logistical support.

References

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APPENDIX E: Permits

REPUBLIC OF KENYA

NATIONAL COMMISSION FOR SCIENCE,TECHNOLOGY & INNOVATION

Ref No: 908516 **Date of Issue: 12/January/2021**

RESEARCH LICENSE

This is to Certify that Mr.. Timothy Downing of University of Nairobi, has been licensed to conduct research in Bungoma, Meru, Nyeri, Transnzoia on the topic: Effect of climate change on biotic patterns and gradients in the tropical alpine moorlands of Mount Kenya and Mount Elgon for the period ending : 12/January/2022.

License No: NACOSTI/P/21/7667

908516

Applicant Identification Number

Director General
NATIONAL COMMISSION FOR SCIENCE,TECHNOLOGY & INNOVATION

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REPUBLIC OF KENYA

NATIONAL COMMISSION FOR SCIENCE,TECHNOLOGY & INNOVATION

Ref No: 762537 **Date of Issue: 08/February/2022**

RESEARCH LICENSE

This is to Certify that Mr.. Timothy Downing of University of Nairobi, has been licensed to conduct research in Bungoma, Meru, Nyeri, Transnzoia on the topic: Effect of climate change on biotic patterns and gradients in the tropical alpine moorlands of Mount Kenya and Mount Elgon for the period ending : 08/February/2023.

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WILDLIFE RESEARCH AND TRAINING INSTITUTE

WRTI/RP/118.6

24th August 2021

Timothy A Downing
Institute for Climate Change and Adaptation
University of Nairobi
P.O. Box 30197 -00100
Nairobi
Email: tarmdowning@gmail.com

Dear Timothy,

Research Permission

We acknowledge your application for a permit to conduct your PhD research approved by the University of Nairobi, titled ***'Biotic effects of Climate changein the tropical alpine moorlands of Mt. Kenya and Mt. Elgon and its impact on dependent local communities'***. You are granted a permit ref No. **WRTI-0004-01-21** to conduct your research **from August 2021 to August 2022** upon payment of the WRTI research fee of **USD 700**.

We hope your study will enhance the understanding of the bio-climatic dynamics of the Alpine zones of Mt Kenya and Mt Elgon, the interactions between local communities and the alpine resources and the implications for community adaptation to climate change in these ecosystems. While conducting your research in Mt Elgon and Mt. Kenya ecosystem, you will comply with the PIC and MAT conditions and the WRTI regulations and guidelines on Wildlife Research within and outside protected areas during your study.

Before commencing your fieldwork you will obtain a NACOSTI permit and discuss the research work plan and reporting with KWS Area Director in-charge of the Mountain and Western Conservation Area (MCA) and the WRTI Principal Scientists (WCA & MCA). You will submit final reports of your research findings to the undersigned.

Yours Sincerely,

DR. PATRICK OMONDI, OGW
AG. DIRECTOR/CEO

Copy to: KWS Director, Parks and Reserves
KWS Assistant Director, MCA
WRTI Principal Scientists, MCA & WCA
WRTI Head Research Permitting & Compliance

WILDLIFE RESEARCH & TRAINING INSTITUTE

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REPUBLIC OF KENYA

THE PRESIDENCY

MINISTRY OF INTERIOR AND COORDINATION OF NATIONAL GOVERNMENT

Telephone: 055- 30326
FAX: 055-30326
E-mail: ccbungoma@yahoo.com
When replying please Quote

Office of the County Commissioner
P.O. Box 550 - 50200
BUNGOMA

REF:ADMIN,15/13.VOL.III/59

3rd March ,2021

TO WHOM IT MAY CONCERN

RE: RESEARCH AUTHORIZATION – TIMOTHY DOWNING

The bearer of this letter, **Timothy Downing** has sought authority to carry out research on, **"Effect of Climate on Biotic Patterns and Gradients in the Tropical Alpine Moorlands of Mount Kenya and Mount Elgon"** for a period ending 30th January 2022.

Authority is hereby granted for the specific period and any assistance accorded to him in this pursuit will be highly appreciated.

Anne N. Wilson
For: County Commissioner
BUNGOMA COUNTY

THE PRESIDENCY

MINISTRY OF INTERIOR AND CO-ORDINATION OF NATIONAL GOVERNMENT

E-mail: nyericountycommissioner@yahoo.com
Telephone: 061 2030619/20
Fax: 061 2032089
When replying please quote

NYERI COUNTY COMMISSIONER
P.O. BOX 33-10100
NYERI

Ref. No. NYC/ADM 1/57.VOL.VII/ (147)

Date: 7th April, 2021

Timothy Downing
University of Nairobi
P O Box 800 - 50204
NAIROBI

RE: RESEARCH AUTHORIZATION

Reference is made to your letter received by our office on 7th April, 2021 on the above subject.

Approval is hereby granted to carry out research on **"Effects of Climate Change on Biotic Pattern's and Gradients in the Tropical Alphine Mo-orlands Mount Kenya and Mount Elgon"** in Nyeri County.

The period of study ends on January, 2022.

M. Kiama
For: County Commissioner
NYERI COUNTY

COUNTY COMMISSIONER
NYERI COUNTY