UNIVERSITY
BAYREUTH

Water and soil management across agricultural land use and climate gradients of Mt. Kilimanjaro

Dissertation

Submitted to the Faculty of Biology, Chemistry and Geosciences of the University of Bayreuth to obtain the degree of Dr. rer. nat

Jerome Kimaro

Bayreuth, April 2021

This doctoral thesis was prepared at the Department of Soil Physics, University of Bayreuth, between April 2014 and April 2021. It was supervised by Prof. Dr. Christina Bogner and Prof. Dr. Bernd Huwe

Date of submission: 03 May 2021

Date of defence: 18 November 2021

Acting dean:Prof. Dr. Benedikt Westermann

Doctoral committee:

Prof. Dr. Christina Bogner (reviewer)

Prof. Dr. Eva Lehndorff (reviewer)

Prof. Dr. Thomas Koellner (chairman)

Prof. Dr. Cyrus Samimi

Prof. Dr. Kelvin Mtei

Abstract

Mountainous agroecosystems are critically important for agricultural production. However, they are increasingly degraded due to human-induced disturbances such as soil erosion, nutrients loss, deforestation, and water loss. Fertile soils and water resources are scarce resources and strongly competed for among farmers to meet their production targets. In consideration of increased human food demands, and rapid land-use conversion, the conservation of mountain agroecosystems deserves special attention to guarantee a sustainable and long-term ecosystem services provision. The objective of this thesis is to analyse the management of soil and agricultural water use in the southern slopes of Mt. Kilimanjaro, with respect to different farming systems and along an elevational gradient. A total of four related studies were conducted: our first two studies analyse the distribution and discharge of irrigation canals and management of agricultural water in the agroecosystem. The third study examines available local knowledge on soil erosion and compares the extent of soil erosion under different farming systems. Finally, the fourth study assesses differences in soil properties under different farming systems and along an elevational gradient in the mountain agroecosystem. To analyse the discharge patterns of traditional irrigation systems, we monitored water flows in canals in eleven locations at different altitudes and during the dry and wet seasons. Canal water levels were recorded three times a day, i.e., in the morning, afternoon, and evening for the duration of eight months. Potential causes responsible for canal flow fluctuations, such as irregular cleaning and blockage, were also recorded. It was found that canals' discharge was nearly twice in the lower compared to the upper elevation zone. The median daily discharges equalled 12.6 l/s, 9.5 l/s, and 7.0 l/s in the lower, mid, and upper areas, respectively. Discharge was also higher during the dry compared to wet seasons. In some villages, canals have changed their annual discharge patterns from perennial to seasonal. An even distribution of canal water among users was not possible due to topographical attributes, in particular terrain ruggedness and slope. Excessive water losses were attributed to excessive water leakage. To analyse the local knowledge about soil erosion management and indicators of soil erosion, a socio-economic survey through Focus Group Discussions (FGDs) was conducted. We found that the majority of local farmers were well-informed about erosion control methods and indicators of soil erosion. However, challenges, such as low income and lack of land ownership, limit their effective participation in sustainable soil management. To analyse patterns of soil erosion, six erosion traps were installed under maize and agroforestry systems. Rainfall, run-off, and sediment losses were monitored during the heavy rainy seasons. Land cover change within crop units employed analysis of Google Earth Pro images. The run off was nearly twice in the lower compared to upper elevation zones under both maize and agroforestry. Run-off decreased significantly in the mid and upper compared to the lower elevation zones (-21.2 l and -17.8 l, respectively). Also, a run-off was significantly higher under maize compared to agroforestry (13.4 l). Sediment loss was three times higher in the lower compared to the upper elevations, and seven times higher under maize compared to agroforestry. Sediment loss decreased slightly between the mid and upper elevation zones (-31.5 g and -31.3 g, respectively), and increased under maize (13.4 g) compared to agroforestry. Rainfall was positively correlated with surface run-off, and the difference was significant between the two farming systems. Farm vegetation was different between the two farming systems: under agroforestry, perennial vegetation cover dominated, with a higher proportion in the upper and mid-elevation zone. Seasonal vegetation cover was dominant under the maize system in the lower elevation zone. Fodder patches and settlement areas indicated only a small proportion under both farming systems. We suggest that current patterns of farm vegetation cover contribute strongly to patterns of surface run-off and sediment loss in the study area. To analyse differences in soil properties, 24 sampling plots were established across different elevational gradients and farming systems It was found that sand content increased, clay content and bulk density decreased with increasing elevation. Soil C and N contents were slightly lower in maize compared to agroforestry, but not soil P. Soil C and N contents increased in the upper compared to the lower elevation zones, while P decreased. The content of cations from CEC showed a heterogeneous picture, the largest difference was that soil Ca and Mg were lower in the upper elevation zones. It was found that spatial variation in soil properties is influenced by both management and hereditary conditions of the soil within the ecosystem. Soil properties are combined in different proportions along an elevational gradient and under different farming systems, which impact soil functions and community well-being differently from one location of the agroecosystem to another. We conclude that the consequences of the current management of agricultural water and soil vary at a spatial scale, thus requiring solutions that are location-specific and prioritized differently. Therefore, farming systems transition in mountainous agroecosystem requires acknowledging the contribution of different knowledge disciplines and reinforcement of multi-stakeholders efforts.

Keywords: *Agroecosystem*, *farmers*, *land-use*, *water*, *soil.*

ZUSAMMENFASSUNG

Gebirgige Agrarökosysteme sind für die landwirtschaftliche Produktion von entscheidender Bedeutung. Sie werden jedoch zunehmend durch vom Menschen verursachte Störungen wie Bodenerosion, Nährstoffverlust, Entwaldung und Wasserverlust gefährdet. Fruchtbare Böden und Wasserressourcen sind unter Landwirten stark umkämpft, um ihre Produktionsziele zu erreichen. Angesichts der gestiegenen Nachfrage nach menschlicher Nahrung, der raschen Veränderung der Landnutzung und des Klimawandels verdient die Erhaltung der Berg-Agrarökosysteme im Zusammenhang mit der Erbringung von Ökosystemleistungen besondere Aufmerksamkeit. Ziel dieser Arbeit ist es, die Bewirtschaftung des Bodens und des landwirtschaftlichen Wasserverbrauchs an den Südhängen des Kilimandscharo im Hinblick auf sich ändernde landwirtschaftliche Systeme und Höhenunterschiede zu analysieren. Insgesamt wurden vier thematisch zusammenhängende Studien durchgeführt. Unsere ersten beiden Studien analysieren die Verteilung von und Abfluss in Bewässerungskanälen sowie die Bewirtschaftung von landwirtschaftlich genutztem Wasser in Agrarökosystemen. Die dritte Studie untersucht das verfügbare lokale Wissen zu Bodenerosion und vergleicht das Ausmaß der Bodenerosion unter verschiedenen landwirtschaftlichen Systemen. Schließlich bewertet die vierte Studie Veränderungen der Bodeneigenschaften unter verschiedenen Anbausystemen und Höhengradienten im Agrarökosystem. Um die Abflussmuster traditioneller Bewässerungssysteme zu analysieren, haben wir an elf Standorten in unterschiedlichen Höhenlagen Wehre installiert und den Kanalabfluss während der Trocken- und Regenzeit gemessen. Die Wehre wurden dreimal täglich, morgens, nachmittags und abends 8 Monate lang abgelesen. Potentielle Ursachen für Abflussschwankungen in den Kanälen wie z.B. unregelmäßige Reinigung und blockierte Kanäle wurden ebenfalls erfasst. Es wurde festgestellt, dass der Abfluss mit abnehmender Höhenlage am Kilimandscharo zunahm. Der Median des täglichen Abflusses betrug 12.6, 9.5 und 7.0 l/s jeweils in der unteren, mittleren und höheren Lage. Zudem war der Abfluss während der Trockenzeit höher als während der Regenzeit. In einigen Dörfern haben Kanäle ihre jährlichen Abflussmuster von mehrjährig auf saisonal geändert. Eine gleichmäßige Verteilung des Kanalwassers unter den Nutzern war aufgrund von topografischen Merkmale, insbesondere aufgrund der Unwägbarkeit des Geländes, nicht möglich. Übermäßige Wasserverluste wurden auf die schwache Struktur nicht ausgekleideter Kanäle, die schlechte Bewirtschaftung, die Durchlässigkeit des Bodens und die übermäßige Leckage zurückgeführt.Um das lokale Wissen über das Bodenerosionsmanagement und die Indikatoren für die Bodenerosion zu verstehen, wurde eine sozialökonomische Umfrage in Form von Fokusgruppendiskussionen (FGDs) durchgeführt. Um die Muster der Bodenerosion zu bestimmen, wurden sechs Erosionsfallen unter Mais- und Agroforstsystemen installiert. Niederschlags-, Abfluss- und Sedimentverluste wurden während starker Regenzeiten überwacht. Die Änderung der Landbedeckung innerhalb der Ernteeinheiten verwendete die Analyse von Google Earth Pro-Bildern. Herausforderungen, geringem Einkommen und mangelndem Landbesitz, die eine wirksame Beteiligung an einer nachhaltigen Bodenbewirtschaftung einschränken. Abfluss und Sedimentverlust nahmen mit abnehmender Höhe zu und unterscheiden sich signifikant zwischen Mais und Agroforst. Der Niederschlag korrelierte positiv mit dem Oberflächenabfluss und der Unterschied zwischen den beiden landwirtschaftlichen Systemen war signifikant. Die Stärke der Beziehung variierte jedoch mit der Höhe. Die Vegetationsbedeckung der landwirtschaftlichen Betriebe zeigte einen scharfen Kontrast zwischen den beiden landwirtschaftlichen Systemen. In der Agroforstwirtschaft dominierte die mehrjährige Vegetationsbedeckung mit einem höheren Anteil in der oberen und mittleren Höhenzone. Die saisonale Vegetationsbedeckung war unter dem Maissystem in der unteren Höhenzone dominant. Futteranbau- und Siedlungsflächen wiesen in beiden landwirtschaftlichen Systemen nur einen geringen Anteil auf. Der Vergleich der Bodeneigenschaften über verschiedene Höhengradienten und landwirtschaftliche Systeme hinweg wurde auf 24 Plots unter Verwendung multivariater statistischer Methoden durchgeführt. Es wurde festgestellt, dass der Sandgehalt zunahm, der Tongehalt und die Lagerungsdichte mit zunehmender Höhe abnahmen. Die Gehalte an C und N waren bei Mais im Vergleich zur Agroforstwirtschaft geringfügig niedriger, nicht jedoch bei P. Die Gehalte an C und N nahmen im oberen Bereich im Vergleich zu den unteren Höhenzonen zu, während P abnahm. Der Gehalt an Kationen aus der Bestimmung der Kationenaustauschkapazität zeigte ein heterogenes Bild, der größte Unterschied waren die Abnahme von Ca und Mg in der oberen Höhenzone. Wir schließen daraus, dass die Folgen der derzeitigen Versorgung mit landwirtschaftlich genutztem Wasser und seiner Abflussdynamik räumlich unterschiedlich sind und daher Lösungen erfordern, die standortspezifisch sind und unterschiedliche Prioritäten setzen. Strukturelle Änderungen, die die Beförderungseffizienz und die Verteilung des landwirtschaftlichen Wassers verbessern würden, sind erforderlich. Das Bewusstsein der Landwirte für Bodenerosion und die Anstrengungen zur Bekämpfung der Bodenerosion stimmen nicht gut überein. Dies zeigt das Vorhandensein verschiedener sozioökonomischer Einschränkungen hinsichtlich ihrer Annahme. Das unterschiedliche Ausmaß des Oberflächenabflusses und des Sedimentverlusts zwischen Mais und Agroforstsystemen zeigt, dass die Landwirte zwischen den beiden Anbausystemen unterschiedliche Ebenen der Bodenbewirtschaftung anbieten. Aktuelle Muster der Vegetationsbedeckung auf dem Bauernhof tragen stark zu Mustern des Oberflächenabflusses und des Sedimentverlusts im Untersuchungsgebiet bei. Die räumliche Variation der Bodeneigenschaften wird sowohl von der Bewirtschaftung als auch von den erblichen Bedingungen des Bodens innerhalb des Ökosystems beeinflusst. Die Bodeneigenschaften werden in unterschiedlichen Anteilen entlang des Höhengradienten und unter verschiedenen Anbausystemen kombiniert, was sich unterschiedlich auf die Bodenfunktionen und das Wohlbefinden der Bevölkerung von einem Ort des Agrarökosystems zum anderen auswirkt. Die Auswirkungen einer nicht nachhaltigen Bewirtschaftung von Boden und Wasser in bergigen Agrarökosystemen könnten mehr sein als in dieser Studie behandelt. Weitere Studien zu menschlichen Aktivitätsmustern bei verschiedenen physikalisch-chemischen Prozessen in der tropischen Berglandwirtschaft sind erforderlich.

Keywords: *Agrarökosystem*, *Landwirtinnen*, *Landnutzung*, *waser*, *boden.*.

Contents

Acknowledgements

First and far most, I would like to express my sincere gratitude to my supervisor, Prof. Dr. Christina Bogner who took a big responsibility that enabled me to carry out this thesis at the Department of Ecological monitoring, BayCEER. Likewise, my co-supervisor, Prof. Dr. Bernd Huwe who visited my field experiment at Mt. Kilimanjaro a couple of times and also offered the opportunity to use facilities at the Soil Physics Department. Furthermore, many thanks to Prof. Dr. Anna Treydte of the Nelson Mandela Institute of Science and Technology, in Arusha, for valuable discussions on statistics and concepts in the preparation of my manuscripts.

In a special way, I am very grateful to my wife Esther and our three cute girls, Noela, Noreen and Nancy to allow me to be away from them for a couple of years when I was way pursuing my research work at Mt. Kilimanjaro and writing the thesis in Bayreuth. Their prayers and patience have been my strength all the time.

I am grateful to all students of KILI Project phase 2 who shared great times at the field station at Nkweseko, especially Emmanuel, Hannes, Anna, Hawa, Joscha, Natalia, Antonia, Henry, Maximillian, just to mention a few. With you, we did not only discuss our research work, but also cultural differences and cooking together. Furthermore, I recognize the great help of field assistants, drivers, and station workers, especially Mr. Fredrik Shoo, Mr. William Nkya, Mr. Wilberd Lyatuu, and Mrs. Veronica Mmari.

I would like to thank my colleagues at Bayreuth for their technical and administrative support. In particular, I acknowledge the great support of Andreas Kolb who was not only useful for guiding the installation of field experiments and laboratory analysis but also engaged me with the local community in Bayreuth through the glass of beer and sports on weekends. Also, I thank Frau Wittke who assisted me with all administrative matters before and after arrival in Bayreuth.

Thanks go to the Germany Research Foundation (DFG) in collaboration with Katholischer Akademischer Auslander-Dienst for the scholarship and financial support to learn the German language. I am also grateful to the authority of the Kilimanjaro National Park (KINAPA) and the Tanzania Wildlife Research Institute (TAWIRI) for facilitating permits for conducting my research work.

Finally, I would like to thank my employer, the Tanzania Wildlife Research Institute (TAWIRI) who granted study leave for me and being away from my duty station for a long period of time.

Chapter 1

Synopsis

1.1 Introduction

1.1.1 Background and motivation

Globally, the importance of mountain agroecosystems needs no emphasis. They host nearly 50% of global biodiversity hotspots (Körner et al., 2005; Ramakrishnan, 2005) and support water-energy-food nexus (Li et al., 2019). Therefore, they are essential for reaching sustainable development goals (SDGs), in particular the reduction of rural poverty and elimination of hunger (Jodha, 2001). Given this consideration, conservation dilemmas in mountain regions are a matter of great concern that calls for critical analysis. Today, the need to protect mountain regions is among a major global agenda (Jodha, 2001), and also emphasized by state macro-policies, in particular agriculture, forest, and water sectors (Komakech et al., 2011; Sokile et al., 2005). However, nearly 7% of mountain areas in developing countries are already covered by crops (Huddleston et al., 2003) and are known to have a significant socio-ecological impact on the management of agroecosystems (Woldesenbet et al., 2018; Sahle and Yeshitela, 2018).

Water and soil are among key land resources that have been contested between different stakeholders in mountain agroecosystems (Viviroli et al., 2020; Bewket and Abebe, 2013). Water demands increase every day compared to the available capacity of their sources (Mwendera et al., 2003). In terms of food production, mountain surface water plays a useful role in supplementing soil moisture during the dry seasons through the use of traditional irrigation canals (Kimaro and Bogner, 2019; Tagseth, 2008). The main features of these infrastructures include long-running unlined canals and gravity-based water flows (Devenne, 2006; Phengphaengsy and Okudaira, 2008). Additionally, they are characterized by excessive water loss and low water conveyance efficiency. Owing to that, the majority of mountain farmers fail to meet their production targets and are frequently engaged in competition with other water users downstream (Haymale et al., 2020; Kimaro et al., 2017).

Soil health in agroecosystem largely depends on how soils are managed (Kibblewhite et al., 2008). For example, soil compaction is a type of soil disturbance caused by frequent driving of heavy equipment in the farm (Hamza and Anderson, 2005; de Graaff et al., 2019). Excessive supply of some essential nutrients could have negative consequences. Nitrogen (N) and phosphorus (P) may be washed through run-off and soil erosion and increase the risk of contaminating water bodies (Rashmi et al., 2017), while cultivation in steep slopes and near water bodies lead to accelerated soil erosion and nutrient loss (Martínez-Mena et al., 2020).

Since hydrological and soil physical properties vary spatially (Jin et al., 2017), indigenous and local knowledge systems in one part of the agroecosystem are not guaranteed to give similar results in the other end. Therefore, scientific approaches are needed to complement farmers' experience in order to deepen the knowledge about soil management and water use across the entire agroecosystem (Tengö et al., 2014).

1.1.2 Threats to mountain agroecosystems

Lack of livelihood alternatives among local farmers compels them to pursue options, some of which are environmentally unfriendly and unlawful, in order for them to survive (Barbier and Hochard, 2018; Mwangi et al., 2018; Sahle and Yeshitela, 2018). Contingent socio-economic and environmental conditions shape farmers' decisions on ways of managing water and soil in agroecosystems.

Failure to seek sustainable solutions to intermittent water supply (Komakech et al., 2011; Sokile et al., 2003) and decreased commitment to repair and maintenance of their canals does not only affect the survival of irrigation canals, but also the overall discharge within catchment (Devenne, 2006). Notably, the degradation of one or a few components within the agroecosystem can have a knock-on effect, causing a further chain of degradation (Turkelboom et al., 2008).

Rapid land use change causes loss of native crops and decrease of vegetation cover (Ficiciyan et al., 2018). Some good practices for soil and water conservation have been ignored or become less practised because of shrinking arable land, complex land tenure, and poverty (Mwango et al., 2016; Soini, 2005). Actions above often lead to the transformation of components' structure and functions in agroecosystems (Kiage, 2013; Gebrelibanos and Assen, 2015). Soil erosion is very responsive to unsustainable land management (Lal, 2017), and would lead to impacts that are either irreversible or involve significant investment cost for restoration (Dimotta, 2019).

Improving soil quality is necessary for protecting soils against degradation and increasing crop yield in agroecosystems. Diversification of farming systems, like the introduction of agroforestry practices, has multiple advantages to the soil. Soils in agroforestry are richer in organic matter, exchangeable cations and water storage. However, farmers need appropriate knowledge on how to select relevant crops and trees that are compatible to the physical condition of the soil, native crops, and local climate. Thus, when agroforestry farms are not well managed, the quality of their soil could severely decrease and closely resemble that of monocropping fields.

1.1.3 A need of interdisciplinary approaches in the management of mountain agroecosystem

Any structural or functional change in the mountain agroecosystem should counter-check a number of merits, including its sensitivity to land degradation, being climate-smart and socially acceptable (Gentle and Maraseni, 2012; Bishaw, 2001). This requires a holistic decision support system that is backed up by multidisciplinary knowledge and collaborative efforts between researchers, local farmers, extension officers, and local administrators (Heneghan et al., 2008; Sokile et al., 2003; Li et al., 2019). Assessing indigenous knowledge reveals how communities are prepared in addressing land degradation risks (Barrera-Bassols and Zinck, 2003). For example, social surveys can help to analyse how human activity patterns contribute to the unwise use of water and soil in the agroecosystem and, in turn, its consequences on local livelihood (Nyangena, 2008). Field and laboratory measurements provide detailed and precise quantification of treatments. For example, soil properties can be used to explain soil hydrological patterns under different agricultural systems (Carter, 1993; Beven et al., 1988). Likewise, the application of remote sensing and geographic information system (GIS) could help to map the distribution of different soil types, irrigation canals, and their relationships to topographical attributes (Jasiewicz and Metz, 2011).

1.1.4 Management of agroecosystems in southern slopes of Mt. Kilimanjaro

Agriculture is the main land use in the southern slopes of Mt. Kilimanjaro. It has long historical background dated back before the independence of Tanzania (Dundas, 1924; Kangalawe et al., 2014). The Chagga people, practising subsistence agriculture, have been the main custodian of the place identity. Crop fields have been managed by traditional-based local knowledge and inherited skills (Soini, 2005). Chagga home gardens, the multi-layered agroforestry systems, with a large variety of food crops and perennial trees are still practised until today especially in the upper elevation zones. The main crops being banana *Musa sp.* and coffee *Coffea arabica* (Soini, 2005; Fernandes et al., 1985). Application of organic amendments, like livestock wastes and crop residues, have been the main source of soil fertility while minimum tillage using hand hoes has been used to control weeds and manipulate soil structure (Kangalawe et al., 2014). Below 1200 m.a.s.l, agroecosystem receive less rainfall (Hemp, 2006a). Traditional irrigation canals have been important for supplementing soil moisture, especially during the dry season. (Devenne, 2006; Tagseth, 2008).

Farming on the slopes of Mt. Kilimanjaro has been acknowledged as one of the best examples of climate-smart agriculture around the world (Palombi et al., 2013). However, this speculation could be no longer the same today in some parts of the agroecosystem. Extensive cultivation of maize (*Zea mays*) and beans (*Phaseolus vulgaris*) in the lower elevation zone is claimed to cause a loss of native vegetation (Hemp, 2006a; Soini, 2005). The shrinking size of home gardens *Kihamba* following rapid human population has put pressure on the access of arable land in the upper elevation zone (Sébastien, 2010;

Soini, 2005). Increased competition of water among key users has affected the discharge capacity of their sources and distribution (Kimaro et al., 2019), while rapid land-use conversion has increased susceptibility to soil erosion and fertility loss (Soini, 2005).

From a scientific point of view, ongoing land-use change on the slopes of Mt. Kilimanjaro offers the opportunity to study how the interaction of human activities and natural factors are responded differently within the mountain agroecosystem. Additionally, to understand what measures could be appropriate for the restoration of soil quality based on local settings.

1.1.5 Objectives

The main objective of this research was to investigate the effects of agricultural land-use change and elevational gradient on water supply and soil properties in the cultivated areas of Mt. Kilimanjaro. Understanding the interaction of human activities and biophysical factors in mountain regions is a prerequisite to cross-check the knowledge gaps between farmers' experience and actual functional processes of soil and water in supporting the provision of various ecosystem services important for agricultural production.

The specific methodological objectives were: (i) To assess the distribution of traditional irrigation canals and to compare canals discharge rates at different elevational zones and different seasons of the year (Manuscript 1) (ii) To assess the potential and the limitations of traditional irrigation systems in mountain agriculture (Manuscript 2) (iii) To quantify and compare the extent of soil erosion under different traditional farming systems and along an elevational gradient (Manuscript 3) (v) To assess available local knowledge and practices applied in the management of soil and water in agroecosystems (Manuscript 2 and 3) (vi) To assess changes in soil properties under different farming systems in agroecosystems (Manuscript 4)

This study provides an in-depth analysis of the state of local uses of agricultural water and soils within smallholder mountain agroecosystems. Since addressing poverty and land degradation remains the primary focus to mountain communities in developing countries, key findings of this study could be applied in other mountain regions of Eastern Africa where climate change, increased human population, and land-use change pose a big threat to the future sustainability of mountain ecosystem and local livelihood.

1.2 Material and methods

1.2.1 Study area and study sites

The cultivated area in the southern slope of Mt. Kilimanjaro is located between 2°45′ and 3°25′S and between 37°00′ and 37°43′E. (Figure 1.1). At the mountain foothills, the colline zone starts around 900 masl up to the submontane zone (1600 - 1800 masl). The area receives bimodal rainfall, whereby the short rains occur between October to December while the long rains start from mid-March, continuing until the end of May (Røhr and Killingtveit, 2003). Three distinct agro-ecological zones, divided according to elevation and rainfall, characterize the study area. The lower area ($<$ 1100 m, mean annual rainfall ranges from 600 to 900 mm) is extensively used for maize monocropping and pastoral livestock grazing. In the mid-elevation zone (1200 - 1350 m, mean annual rainfall ranges from 1800 to 2000 mm), the dominant farming system consists of coffee-banana agroforestry while in the upper area (1350 - 1600 m, mean annual rainfall ranges from 1000 to 1200 mm), is dominated by traditional home gardens agroforestry (Fernandes et al., 1985; Soini, 2005). The landscape is mainly dominated by volcanic soils, i.e., in the upper areas mainly Leptosols (Borrelli et al., 2017; IUSS Working Group WRB, 2015), whereas in the plains mainly Vertisols, Ferralsols, and Nitisols (Zech et al., 2014).

To obtain sampling sites, all villages located in the cultivated area of Mt. Kilimanjaro were obtained from the Land Planning Units at Moshi and Hai District Councils. Stratified multistage sampling (Jain and Hausman, 2014) was applied to classify villages based on their location along the elevational gradient and based on the dominant farming systems. Firstly, villages were allocated based on the major agroecological zones, i.e., the lower, mid, and upper elevation zones. Secondarily, under each elevational zone, only villages that access irrigation canals were selected. Thirdly, villages that practice agroforestry were separated from those practising maize farming. Finally, To compare findings along the mountain elevation gradient, the sampling plots were organized in four transects running from the lower (900 masl) to the upper area (1600 masl), thus making a total of 24 study villages across the whole agroecosystem. In each village, one sampling plot (1 ha) was established based on the Land Degradation Surveillance Framework (LDSF) (Vågen et al., 2010).

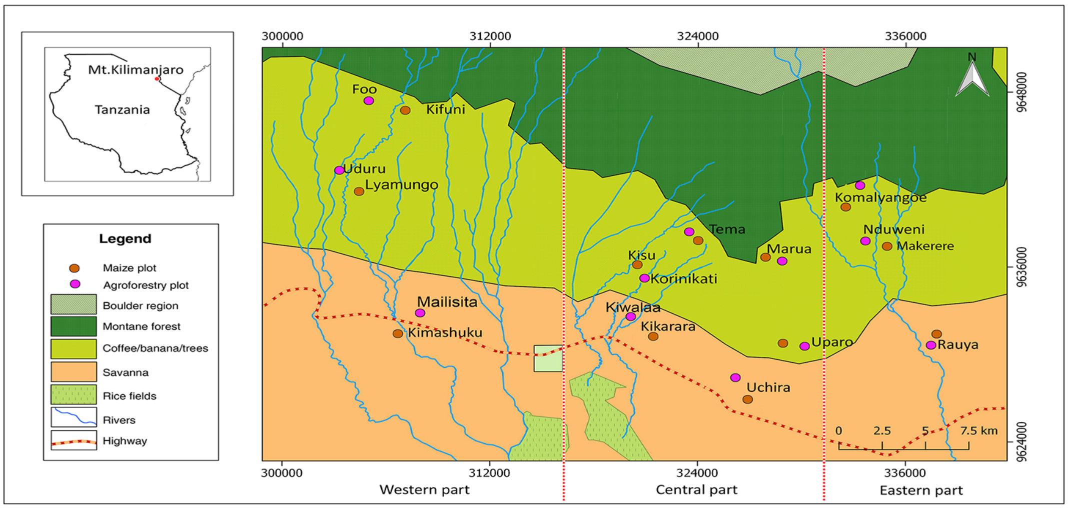

Figure 1.1: The study area (Google Maps, 2017), i.e., Southern slopes of Mt. Kilimanjaro and its main vegetation zones (Hemp, 2006c). Circles indicate plot locations dominated by two different agricultural management typesi.e., maize and agroforestry systems.

1.2.2 Analysis of canal discharge dynamics (Manuscript 1)

A network of eleven 60° V notch weirs was established. We used the concept of citizens' science (Brossard et al., 2005) and developed a protocol in which 11 villagers were trained to read the weirs, monitor, and report various causes of discharge fluctuations in canals. The discharge was recorded three times a day (morning, afternoon, and evening) from June 2015 to February 2016, after the end of the long rainy season (from March to June). Furrow discharge was computed by KindsvaterShen equation (Shen, 1981). To determine the current status of canals, we asked members of village water committees to conduct a survey in their respective villages and to report on (i) the total number of present canals, (ii) their flow status (dried, perennial, or seasonal) and (iii) their major sources.

Figure 1.2: Measuring canal discharge using 60° V-notch weir (A) A farmer irrigating using traditional canal in a new vegetable field (B)

1.2.3 Analysis of soil physical and hydraulic properties (Manuscript 1, 3 and 4)

Soil particle distribution was assessed as a proxy indicator for water permeability, vulnerability to erosion, and root growth (Passioura, 2002). We collected 300 g of bulk soil samples from the top 30 cm soil in each subplot. Samples were air-dried and sieved < 2 mm. Organic matter was removed by hydrogen peroxide in a hot water bath. The sand was determined by wet sieving (Carter and Gregorich, 2008) and fractions of clay, silt, and fine sand by sedimentation using PARIO equipment (Durner et al., 2017). Additionally, we assessed soil bulk density (BD) to determine the effect of tillage on soil structure and vulnerability to surface run-off. Undisturbed soil cores were collected at a depth of 30 cm and weighed before and after drying to constant weight at 105 °C (Heuscher et al., 2005). Volumetric water content (VWC) was determined by multiplying the gravimetric water content by the bulk density. Soil saturated hydraulic conductivity (K_{sat}) was determined by the double ring method in order to determine the susceptibility of percolation losses in unlined canals.

Figure 1.3: A 30 cm soil sampling pit (A), measuring of soil texture using PARIO Equipment (B), measuring soil hydraulic conductivity using double ring method (C)

1.2.4 Terrain analysis (Manuscript 1)

This was conducted to determine the influence of topography on hydrological processes, in particular stream networks and soil moisture storage. The advanced Space Born Thermal Emission and Reflection Radiometer (ASTER) Digital Elevation Map (DEM) with 30 m resolution was downloaded from the USGS website (https://earthexplorer.usgs.gov). Within the QGIS environment, r.watershed and r.slope.aspects modules were used to compute the Topographic Wetness Index (TWI) and the drainage direction (Dd). Furthermore, slope (S) and terrain roughness (TRI) were computed by using the terrain analysis plug-in.

1.2.5 Analysis of soil chemical properties (Manuscript 4)

Soil chemical analysis was conducted to determine the variation of soil nutrients between agroforestry and maize systems. Five essential plant nutrients, namely nitrogen (N), phosphorus (P), calcium (Ca), magnesium (Mg), and potassium (K), and the beneficial element sodium (Na) were assessed. Additionally, cation exchange capacity (CEC) and base saturation (CEC_{sat}) for all samples were measured. Total soil N was determined by using CHN analyser (Thermo Quest, Flash EA, 1112 model) (Jimenez and Ladha, 1993). Available P was first extracted by using Calcium-Acetate-Lactate (CAL)(van Laak et al., 2018) and then its concentration was measured by using the inductively coupled plasma optical emission spectroscopy (ICP-OES, Varian Vista Pro model, Varian Inc. The Netherlands) (Maguire and Sims, 2002). Additionally, all exchangeable cations (Mg, Na, K, and Ca) were extracted with ammonium chloride solution, then their concentrations were measured by ICP-OES (König et al., 2005).

1.2.6 Analysis of surface run-off and sediment loss (Manuscript 3)

We compared the extent of soil erosion between maize and agroforestry farming systems through monitoring run-off and sediment losses at a plot scale in six representative plots, namely Foo, Kifuni, Uduru, Lyamungo, Kimashuku, and Mailisita (Figure 1.1). Both maize and agroforestry plots were replicated into three plots along an elevation gradient. Erosion traps measuring 30 m^2 were installed in each study plot without disturbing the virginal condition of the farms. The run-off was collected in a 150-liter barrel. Rainfall gauges were installed near the erosion plots, but free of higher tree canopies. Data was collected on a cumulative basis every two days. Rainfall volume was measured by using a measuring cylinder, whereas run-off volume was computed based on its height inside the barrel and the cross-sectional area of run-off (Zdravkovich, 1997). The run-off mixture was vigorously stirred before the collection of 0.5-liter sub-samples. The collected samples were oven-dried at 105 °C and re-weighted until constant weight.

Figure 1.4: Soil erosion trap (A) rain gauge (B)

1.2.7 Analysis of farm land-use change (Manuscript 3)

We analysed major types and coverage of farm land-use types characterizing maize and agroforestry systems. Observations were conducted in similar farm plots where erosion plots were installed. Aerial images of the same plots were captured using Google Earth-Pro application. Visual interpretation of land-use types was conducted, followed by a field visit for ground-truthing (Tilahun and Teferie, 2015). The images were exported to Photoshop CS 6 graphics editor software. Hand sketching tools were used for delineation, identified cover types. The grid tool was used to estimate the proportion of each cover type. The approach mimicked the traditional quadrant pantograph techniques (Hill, 1920). Finally, we applied an object-based classification approach (Hill, 1920) to categorize identified land-use types into the following distinct groups: (i) Perennial cover comprised of areas covered by higher trees, banana, and coffee plants (ii) Seasonal cover comprised of the areas growing maize and beans (iii) fodder cover comprised of areas growing grass (iv) settlement areas involved all built structures in the farms. The proportion of each land cover above was quantified and presented in percentage.

1.2.8 Analysis of socio-economic information (Manuscript 1, 2 and 3)

Socio-economic information from villagers was analysed to gain insights about available local knowledge related to the management of agricultural water, soil erosion, and improving soil quality. Various participatory approaches were used to collect qualitative information (Rust et al., 2017).

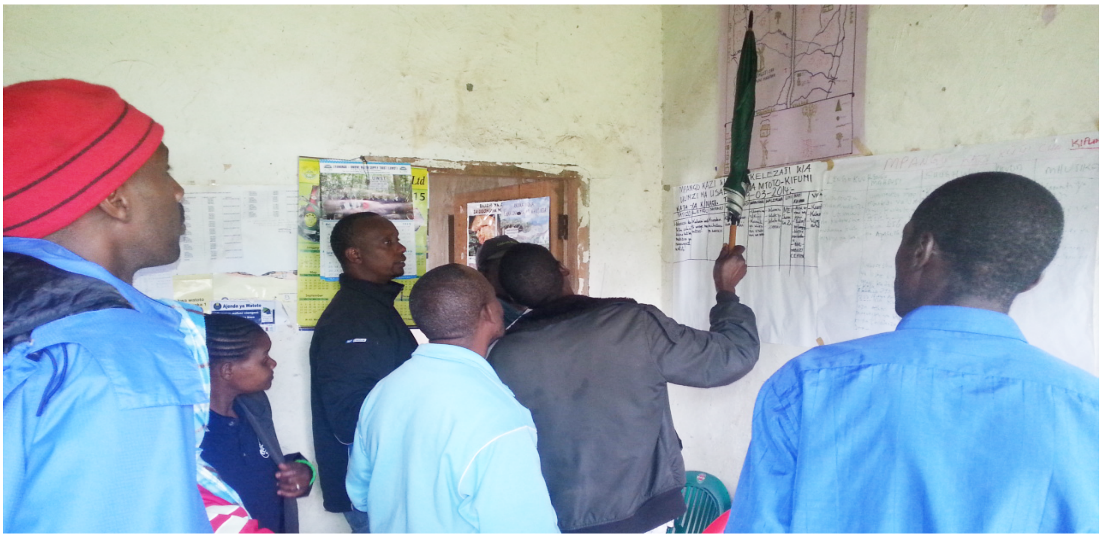

Figure 1.5: Villagers showing distribution map of tradition irrigation canals in one of surveyed village.

Focus Groups Discussions (FGDs) involved a small group of villagers (n = 10 - 15). The meetings were attended by diverse social groups like women, elderly people, and leaders to obtain a good representation of their communities (Kitzinger, 1994). The aim of FGDs was to gather in-depth insights about local perceptions, attitudes, and opinions of villagers in relation to the management of water and soil in agricultural production.

Key informants (KI) surveys involved one-to-one consultation with selected individuals for discussion about very specific topics related to the management of water and soil in the study area. Officials from district councils including agricultural, forest, and irrigation experts. These consultative meetings aimed at opportunities and barriers of institutional linkages between the district and local communities towards sustainable management of water and soil in the study area. Additionally, we conducted meetings with the Pangani Basin Water Office (PWBO) to assess stakeholders' compliance with water use regulations and assess initiatives implemented by the central government in reducing natural resource degradation at the basin level.

Participatory resources mapping technique (Tripathi and Bhattarya, 2004), was used to guide the community to develop a hand sketch map of their irrigation schemes. Villagers were divided into three small groups of participants (n = 3-5) to brainstorm their ideas. Villagers' knowledge about the scheme structure was presented on a piece of paper by each group based on the following criteria: (i) canals intake sources, (ii) routes of primary, secondary and tertiary canals, (iii) orientation of crop fields. Presented ideas were combined into one final version that was agreed upon by all participants. The map was then scanned and imported into the computer to develop new vector layers based on the details of the villagers' hand-sketched map. All graphics work was completed by using Adobe Illustrator software, version CS 6 (Bautrénas et al., 2006).

1.3 Results and discussion

1.3.1 Distribution, discharge and structure of irrigation canals

The patterns of agricultural water supply in agroecosystem indicates that discharge and distribution of traditional irrigation canals could be varying across the study villages. This is attributed to the unique combination of biophysical and management factors. Land morphology is characterized by different slope angles and surface roughness, thus determining the flow direction of the discharge (Beven et al., 1988). Additionally, the length of the canal is an important aspect of water distribution. To increase the chance of reaching distant villages down the slope, more than one primary canal has been combined. However, it strongly responds to soil physical properties that determine the permeability and workability of the soil. Where soils are highly permeable, percolation loss exceeds run-off (Schreiner-McGraw and Vivoni, 2018). Our field findings indicated that most irrigation canals have been constructed where soil hydraulic conductivity (Ksat) indicated low to moderate values. Likewise, key informants informed that locations where soil are highly permeable have been avoided to construct canals (Pers. Comm). Observations above reveal that our empirical findings on canal water supply fit well with available local knowledge.

The current management of agricultural water in the slope of Mt. Kilimanjaro could affect water use efficiency starting from individual farm plots up to basin level. This implies that management challenges related to water are not in the hands of smallholder farmers alone, but also within water management institutions. Among basin managers, the proportion of water used to sustain mountain farming versus that flowing out of the catchment is often not known(Røhr and Killingtveit, 2003). Additionally, a top-down management approach applied by district officials (Kangalawe et al., 2014) provides less room for local knowledge and skills being integrated into planning and decision-making. Therefore, it could be challenging to strategies sustainable water management and equitable sharing among different users.

At the scheme level, canals are the main source of water for agricultural production. Opportunities to exploit groundwater, pumping water from rivers, or harvesting rainwater as a substitute to canals has been less practised around Mt. Kilimanjaro (Devenne, 2006). To sustain canals' water supply into schemes, we found that micro-dams (*Nduwa*) have been integrated as part of the canal network. According to local farmers, these structures enhance constant discharging of weak sources that could otherwise fail not maintain their discharge if they were directly released to farm plots. However, a full commitment to the maintenance of micro-dams is highly lacking, thus affecting their water holding capacity. This implies that farmers could improve water availability in the schemes without increasing water abstraction at canal sources.

Under different farming systems, canals have been managed differently. Increased canal size and their discharge rates in the lower elevation zone, probably related to higher demand for commercial vegetable production and off-season maize growing (Kimaro et al., 2019; Soini, 2005). Less number of canals were reported to operate under agroforestry, and in the upper elevation zone (Pers. Comm). Probably, attributed to better soil moisture storage under agroforestry (Jose, 2009). Likewise, the upper elevation zone of the agroecosystem receives frequent precipitation (Hemp, 2006b). However, two concerns will remain unsolved if the present management of canals will remain unchanged. Because the conveyance of canal water is gravity-driven, villages located on hilly sides will continue to rely on rain-fed agriculture. Secondly, since a large amount of canal water is lost through deep percolation and leakage, available water will not meet the increased demands of downstream users.

1.3.2 Local knowledge about soil erosion

The existing local knowledge about soil erosion indicated that communities in the slopes of Mt. Kilimanjaro are well-informed about indicators and measures of controlling soil degradation. This could be related to multi-decadal involvement in agricultural practices (Soini, 2005).

Good practices of soil management around Mt. Kilimanjaro seem to decrease over time. This implies that communities could be facing a number of socio-economic limitations. For example, higher preference towards soil conservation practices that involve less manpower and low investment cost were reported. Furthermore, a challenging land tenure system could also be a potential barrier to improved land management in the study area. It was reported that customary laws provide fewer opportunities for women in making a decision about the management of inherited land (Pers. Comm). Similarly, those who rented land avoid heavy capital investment in establishing permanent soil conservation measures when the tenure period is not guaranteed (Pers. Comm). Our observations concur well with reports from other developing countries whereby soil conservation under smallholder farming face multiple barriers (Pilgrim et al., 2018; Chapagain and Raizada, 2017; Nahayo et al., 2016). Therefore, tapping into local knowledge and experiences could be used as a potential alternative to generate perceived patterns of soil erosion under smallholder farming.

1.3.3 Changes in farm land-use

Current patterns of farm vegetation cover indicated that the proportion of land-use types varied between farming systems and across an elevational gradient. Under the agroforestry system, the perennial cover type comprised of higher trees, banana, and coffee plants was dominant. The larger proportion was located in the upper and mid (83.5%, 76.2%, respectively) compared to the lower elevation zone (55%). Probably, perennial cover land-use type offers the strongest resistance against surface run-off and sediment loss process across all study plots. Studies have reported that farms with multi-strata canopy structural are known to suppress the high kinetic energy of the raindrops before reaching the ground (Suprayogo et al., 2020; Kuyah et al., 2017). Fodder cover type was only located in the upper and mid-elevation zones. Its distribution is probably influenced by higher demand for livestock feed in this part of agroecosystem (Kimaro, 2019). Although fodder plants provide a protective effect against splash and rain-impacted erosion (Ha et al., 2012), it constitutes only a very small proportion (between 4.5% and 9%) in the study area. Under the seasonal vegetation cover, the dominant crops across all three elevation zones were maize and bean crops. The highest proportion was in the lower (96%) followed by the mid (87%) while the least was in the upper elevation zone (75%). The soil under seasonal vegetation cover could be very vulnerable to soil erosion risk because canopies are very porous. Although beans are a cover crop, they could only provide limited resistance against soil erosion. Our field observation noted splashed particles and rill channels even where beans were grown. Similar observations have been reported from the highlands of Kenya, whereby more run-off and sediment loss were produced when maize was intercropped with beans compared to cowpeas (Kariaga, 2004). This suggests that, if bean remains a traditional crop to farmers around Mt. Kilimanjaro, other efficient cover crops should be integrated with maize. For example, intercropping maize-wheat rotation has indicated increased farmers' income and reduced soil erosion in Himalaya, India (Sharma et al., 2017).

1.3.4 Surface run-off and sediment loss under different farming systems

The correlation between rainfall and run-off was significant under both farming systems and along the elevational gradient. Probably, rainfall play important role in the occurrence of soil erosion in the study area.

The extent of surface run-off and sediment loss varied between farming systems and across elevational gradients. Run-off decreased significantly in the mid and upper compared to the lower elevation zones (-21.2 l and -17.8 l, respectively). Moreover, a larger amount of run-off was collected under maize (13.4 l) compared to agroforestry. We relate the differences above to variability in farm land-use types and their coverage. Furthermore, we suggest that higher rates of sediment loss under the maize system could be related to types of agronomic activities, of which some are unique from agroforestry. Because of delayed sawing, only a small proportion of soil surface is covered by young maize plants before the starting of rainfall. Thus, a large proportion of loose soil washed away. Even after growing maize plants, routinely uprooting weeds removes ground cover that could be an important cushion layer against raindrops. Moreover, the application of mechanical tillage is suspected to increase soil compaction under the maize system. High levels of soil bulk density and low hydraulic conductivity have been reported in the lower elevation zone of Mt. Kilimanjaro, where maize cropping is dominant (Kimaro et al., 2019). Farms with compacted soil experience higher rates of surface run-off and sediment loss (Hamza and Anderson, 2005; Keller et al., 2019).

A slight difference in sediment loss between the mid and upper elevation zones (-31.5 g and -31.3 g, respectively) suggests that farm land-use types in these locations offer a comparable mechanism of preventing soil erosion. Banana-coffee system in the mid-elevation zone (O'Kting'ati and Kessy, 1991) and traditional home-gardens in the upper elevation zone (Soini, 2005) are comprised of multi-layered canopies. Probably, similar hydrological processes like through fall, interception, steam-water flow, are happening under these land-use covers.

1.3.5 Changes in soil physical and chemical properties

The analysis of soil physical properties indicated high heterogeneity in the study area. Probably, these changes are influenced by different parental material or different management practices among farmers. In this study, changes of soil sand and clay contents with elevation could be strongly related to the nature of parental material rather than the effect of management. Indeed, soil texture is relatively homogeneous across the same slope because they are static in nature (Carter and Gregorich, 2008). Therefore, we could not expect significant changes in soil particles distribution between different farming systems.

Increasing soil BD under maize system and variability of VWC under agroforestry is a good example of how changes in management practices affect soil physical properties. This implies that plots under the maize system could be more vulnerable to soil compaction, while the soil in the lower elevation could only sustain drought-resistant crops. Normally, compacted and dried soil limits proper seed germination, root growth, and increased soil erosion risks (Udom and Ehilegbu, 2018; Shah et al., 2017).

A slight difference in soil C and N contents between maize and agroforestry system suggest that most agroforestry plots could be nutrient deficient. Probably, this reflects a decreased commitment among farmers to maintaining good practices for land management. Under normal circumstances, agroforestry farms retain higher content of soil C and N (Querné et al., 2017; Muchane et al., 2020; Jose, 2009). We suggest that ongoing uprooting of coffee plants and introduction of non-native trees species (Soini, 2005; Maghimbi, 2007) around Mt. Kilimanjaro could have affected nutrient cycles and soil water storage. However, our data set is relatively small and shows a large variability. Furthermore, decreased amount of soil P content in the upper elevation zone could be related to high sand content and not management practices. Sandy soils have high P buffering capacity (Frossard et al., 1992). Likewise, high soil moisture content influences its adsorption (Sun et al., 2020).

Changes in exchangeable cations explain that the distribution of negative charges ions are influenced by both elevation and farming system. For example, decreased Ca and Mg in the upper compared to the lower (-1191 mg kg^{-1} and -458 mg kg^{-1}, respectively) could be influenced by decreased clay content in the upper elevation zone, thus attracting and holding a large number of positive cations (Hartemink, 2016). Decreased CEC in the upper elevation zone implies that the use of soluble inorganic fertilizers should be used with great precautions to avoid excessive loss through over-irrigation or during a long rain season. This effect could lead to environmental pollution and economic loss to farmers (Masmoudi et al., 2020).

The assessment of four principal components (PCs) has shown that the largest variability in the data set is due to the elevation and there is little separation of data points depending on the farming system. Therefore, overlaps between farming systems or elevation gradients exist in variable degrees. Variations explained by PC1 indicated an increase of N and C contents in the upper elevation, which implies that the crop production potential under home gardens (O'Kting'ati and Kessy, 1991) could be far above those in mid and lower elevation zones. Variations in PC2 indicate that increased clay content and soil BD could lead to compacted soil under both maize and agroforestry farms. The same observations have been reported in other studies (Hamza and Anderson, 2005). Increasing soil permeability, as explained by PC3, suggests that soils in the upper and mid-elevation zones are more permeable, thus could minimize surface run-off and being appropriate for the production of root crops (Colombi et al., 2018). Information indicated by PC4 suggests that the increase of Na in the upper elevation zone could be strongly influenced by underlying parental material rather than management activities.

1.4 Conclusions and recommendations

In four different studies, this thesis analysed the major factors and processes that govern the management of soil and agricultural water under different farming practices in the southern slopes of Mt. Kilimanjaro. The focus of the first two studies was the management implications of irrigation canals and small schemes on their distribution, discharge, and water sharing. In the third study, we focused on the relationship between local knowledge on soil management, farm land-use pattern, and current patterns of soil erosion in agroecosystems. The last study assessed changes in soil properties under different farming systems to observe soil heterogeneity in agroecosystems. The following four sections summarize the main findings, present their limitations, and provide recommendations for future research.

Study one: Canals density was not evenly distributed in the landscape because of both biophysical and management factors. Moreover, there is a limited possibility to expand the size of the canal network around Mt. Kilimanjaro. We conclude that dependency on a gravity-based water supply system will not suffice water needs unless other sources, like boreholes, pumping river water, or rainwater harvesting, will be established as substitutes. Thus, the hypothesis formulated for this study can be confirmed.

Study second: The results demonstrated that the unsustainable management of agricultural water is influenced by multiple responses, in particular conflicting sectoral policies, land tenure system, and land-use change. We can conclude that promoting integrated water management in the slopes of Mt. Kilimanjaro could offer promising solutions towards sustainable water use. Therefore, the second hypothesis formulated for this study must be accepted.

Study three: Results showed that available local knowledge did not match well with efforts invested in controlling soil erosion. Land-use types were highly variable under different farming systems and elevational gradients. Changes in soil erosion were more pronounced between different farming systems compared to the elevational gradient. We conclude that the extent of run-off and sediment loss is strongly influenced by farmland use and management practices. Therefore, we reject hypothesis 1 and 2, but only hypothesis 3 is accepted in this study.

Study four: Soil properties indicated high heterogeneity under different farming systems and elevational gradients. Data variability indicated overlap between farming system and elevational gradient across each agroecological zone. We conclude that agricultural production potential in the agroecosystem of Mt. Kilimanjaro varies from one location to another, thus affecting food security and income differently. Therefore, the first hypothesis for this study is accepted while the second is rejected.

1.5 Records of contributions to the included manuscripts

Table 1.1: Manuscript 1: Distribution of traditional irrigation canals and their discharge dynamics at the southern slopes of Mt. Kilimanjaro (Published in Frontier in Environment Science. https://doi.org/10.3389/fenvs.2019.00024)

Co-author	Contribution (%)	Details
Jerome Kimaro	45	Experimental design, field sampling, data preparation and analysis, writing manuscript
Valeska Scharsich	10	Data analysis and writing manuscript, corresponding author
Andreas Kolb	5	Experimental design, field sampling
Bernd Huwe	5	Experimental design and writing manuscript
Christina Bogner	35	Experimental design, data analysis and writing manuscript

Table 1.2: Manuscript 2: Water management under traditional farming systems: Practices and limitations of the Mfongo system around Mt. Kilimanjaro (Published in Water Utility Journal 22: 53-64, 2019)

Co-author	Contribution (%)	Details
Jerome Kimaro	80	Experimental design, field sampling, data preparation and analysis, writing manuscript
Christina Bogner	20	Experimental design and writing manuscript

Table 1.3: Manuscript 3: Soil erosion under different farming systems on Mt. Kilimanjaro (Not yet submitted)

Co-author	Contribution (%)	Details
Jerome Kimaro	70	Experimental design, field sampling, data preparation and analysis, writing manuscript
Andreas Kolb	10	Experimental design, field sampling
Bernd Huwe	5	Experimental design and writing manuscript
Christina Bogner	15	Experimental design, data analysis and writing manuscript

Table 1.4: Manuscript 4: Variability of soil properties under different farming systems on Mt. Kilimanjaro (Submitted in Agroforestry Systems Journal- Springer)

Co-author	Contribution (%)	Details
Jerome Kimaro	50	Experimental design, field sampling, data preparation and analysis, writing manuscript
Anna Treydte	10	Writing manuscript
Bernd Huwe	5	Experimental design and writing manuscript
Christina Bogner	35	Experimental design, data analysis and writing manuscript

Published data

We published our data in PANGAEA website (www.pangae.de), a data publisher for earth and environmental science. A total of four data sets were published.

1. Kimaro, Jerome Gadi, Bernd Huwe, and Christina Bogner (2020). “Physical soil properties in agroecosystem around Mt. Kilimanjaro”.https://doi.org/10.1594/PANGAEA.918660.

2. Kimaro, Jerome Gadi, Bernd Huwe, and Christina Bogner (2020). “Supply and discharge dynamics of irrigation canals around Mt. Kilimanjaro”. https://doi.org/10.1594/PANGAEA.918658.

3. Kimaro, Jerome Gadi, Bernd Huwe, and Christina Bogner (2020). “Chemical soil properties in agroecosystem around Mt. Kilimanjaro”. https://doi.org/10.1594/PANGAEA.918659.

4. Kimaro, Jerome Gadi, Bernd Huwe, and Christina Bogner (2020). “Soil erosion around Mt. Kilimanjaro” https://doi.org/10.1594/ PANGAEA.918661.

Bibliography

Barbier, E. B. and Hochard, J. P. (2018). Land degradation and poverty, *Nature Sustainability* **1**(11): 623–631.

Barrera-Bassols, N. and Zinck, J. A. (2003). Ethnopedology: a worldwide view on the soil knowledge of local people, *Geoderma* **111**(3-4): 171–195.

Bautrėnas, A., Konstantinova, J. and Pileckas, M. (2006). Estimation and improvement of scanned map quality (in basis of adobe photoshop), *Geodesy and Cartography* **32**(1).

Beven, K. J., Wood, E. F. and Sivapalan, M. (1988). On hydrological heterogeneity – catchment morphology and catchment response, *Journal of hydrology* **100**(1-3): 353–375.

Bewket, W. and Abebe, S. (2013). Land-use and land-cover change and its environmental implications in a tropical highland watershed, ethiopia, *International journal of environmental studies* **70**(1): 126–139.

Bishaw, B. (2001). Deforestation and land degradation in the ethiopian highlands: a strategy for physical recovery, *Northeast African Studies* pp. 7–25.

Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V. et al. (2017). An assessment of the global impact of 21st century land use change on soil erosion, *Nature communications* **8**(1): 2013.

Brossard, D., Lewenstein, B. and Bonney, R. (2005). Scientific knowledge and attitude change: The impact of a citizen science project, *International Journal of Science Education* **27**(9): 1099–1121.

Carter, M. and Gregorich, E. (2008). Soil sampling and methods of analysis. 2nd, *Can. Soc. Soil Sci* **1224**.

Carter, M. R. (1993). *Soil sampling and methods of analysis*, CRC Press.

Chapagain, T. and Raizada, M. N. (2017). Agronomic challenges and opportunities for smallholder terrace agriculture in developing countries, *Frontiers in Plant Science* **8**: 331.

Colombi, T., Torres, L. C., Walter, A. and Keller, T. (2018). Feedbacks between soil penetration resistance, root architecture and water uptake limit water accessibility and crop growth–a vicious circle, *Science of the total environment* **626**: 1026–1035.

de Graaff, M.-A., Hornslein, N., Throop, H. L., Kardol, P. and van Diepen, L. T. (2019). Effects of agricultural intensification on soil biodiversity and implications for ecosystem functioning: a meta-analysis, *Advances in Agronomy*, Vol. 155, Elsevier, pp. 1–44.

Devenne, F. (2006). On 'the mountain of waters', the furrows are running dry: Rethinking mount kilimanjaro's irrigation system, *Kilimanjaro. Mountain, Memory, Modernity* pp. 201–214.

Dimotta, A. (2019). Global soil erosion costs: a critical review of the economic assessment methods, *Soil erosion interdisciplinary overview: modelling approaches, ecosystem services assessment and soil quality restoration. applications and analyses in the Basilicata region. Italy. Retrieved from https://doi. org/10.13140/RG* **2**(13842.30401).

Dundas, C. (1924). Kilimanjaro and its people : A history of the wachagga, their laws, customs and legends, together with some account of the highest mountain in africa, *Technical report*, H.F & G Witherby.

Durner, W., Iden, S. C. and von Unold, G. (2017). The integral suspension pressure method (isp) for precise particle-size analysis by gravitational sedimentation, *Water Resources Research* **53**(1): 33–48.

Fernandes, E. C., Oktingati, A. and Maghembe, J. (1985). The chagga homegardens: a multistoried agroforestry cropping system on mt. kilimanjaro (northern tanzania), *Agroforestry systems* **2**(2): 73–86.

Ficiciyan, A., Loos, J., Sievers-Glotzbach, S. and Tscharntke, T. (2018). More than yield: Ecosystem services of traditional versus modern crop varieties revisited, *Sustainability* **10**(8): 2834.

Frossard, E., Fardeau, J., Ognalaga, M. and Morel, J.-L. (1992). Influences of agricultural practices, soil properties and parent material on the phosphate buffering capacity of cultivated soils developed in temperate climates, *European Journal of Agronomy* **1**(1): 45–50.

Gebrelibanos, T. and Assen, M. (2015). Land use/land cover dynamics and their driving forces in the hirmi watershed and its adjacent agro-ecosystem, highlands of northern ethiopia, *Journal of Land Use Science* **10**(1): 81–94.

Gentle, P. and Maraseni, T. N. (2012). Climate change, poverty and livelihoods: adaptation practices by rural mountain communities in nepal, *Environmental science & policy* **21**: 24–34.

Ha, H. A. P., Huon, S., des Tureaux, T. H., Orange, D., Jouquet, P., Valentin, C., De Rouw, A. and Duc, T. T. (2012). Impact of fodder cover on runoff and soil erosion at plot scale in a cultivated catchment of north vietnam, *Geoderma* **177**: 8–17.

Hamza, M. and Anderson, W. (2005). Soil compaction in cropping systems: A review of the nature, causes and possible solutions, *Soil and tillage research* **82**(2): 121–145.

Hartemink, A. E. (2016). Scheffer/schachtschabel soil science., *Soil Science Society of America Journal* **80**(2): 528–528.

Haymale, H. K., Njau, K. N. and Kahimba, F. C. (2020). Estimating conveyance efficiency and maize productivity of traditional irrigation systems in usa river catchment, tanzania, *International Journal of Agronomy* **2020**.

Hemp, A. (2006a). Continuum or zonation? altitudinal gradients in the forest vegetation of mt. kilimanjaro, *Plant ecology* **184**(1): 27–42.

Hemp, A. (2006b). Ecology and altitudinal zonation of pteridophytes on mt. kilimanjaro, *African Plants: Biodiversity, Ecology, Phytogeography and Taxonomy* .

Hemp, A. (2006c). Vegetation of kilimanjaro: hidden endemics and missing bamboo, *African Journal of Ecology* **44**(3): 305–328.

Heneghan, L., Miller, S. P., Baer, S., Callaham Jr, M. A., Montgomery, J., Pavao-Zuckerman, M., Rhoades, C. C. and Richardson, S. (2008). Integrating soil ecological knowledge into restoration management, *Restoration Ecology* **16**(4): 608–617.

Heuscher, S. A., Brandt, C. C. and Jardine, P. M. (2005). Using soil physical and chemical properties to estimate bulk density, *Soil Science Society of America Journal* **69**(1): 51–56.

Hill, R. R. (1920). Charting quadrats with a pantograph, *Ecology* **1**(4): 270–273.

Huddleston, B., Ataman, E., De Salvo, P., Zanetti, M., Bloise, M., Bel, J., Francheschini, G. and Fed'Ostiani, L. (2003). Towards a gis-based analysis of mountain environments and populations, *Environment and Natural Resources working paper* **10**.

IUSS Working Group WRB (2015). *World Reference Base for Soil Resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps*, World Soil Resources Reports No. 106. FAO, Rome.

Jain, A. K. and Hausman, R. E. (2014). Stratified multistage sampling, *Wiley StatsRef: Statistics Reference Online* .

Jasiewicz, J. and Metz, M. (2011). A new grass gis toolkit for hortonian analysis of drainage networks, *Computers & Geosciences* **37**(8): 1162–1173.

Jimenez, R. and Ladha, J. (1993). Automated elemental analysis: A rapid and reliable but expensive measurement of total carbon and nitrogen in plant and soil samples, *Communications in Soil Science and Plant Analysis* **24**(15-16): 1897–1924.

Jin, Z., Azzari, G., Burke, M., Aston, S. and Lobell, D. B. (2017). Mapping smallholder yield heterogeneity at multiple scales in eastern africa, *Remote Sensing* **9**(9): 931.

Jodha, N. (2001). Sustainable agriculture in fragile resource zones: technological imperatives, *in* N. Jodha (ed.), *Life on the Edge: Sustaining Agriculture and Community Resources in Fragile Environments*, Oxford University Press, New Delhi.

Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: an overview, *Agroforestry systems* **76**(1): 1–10.

Kangalawe, R., Noe, C., Tungaraza, F., Naiman, G. and Mlele, M. (2014). Understanding of traditional knowledge and indigenous institutions on sustainable land management in kilimanjaro region, tanzania, *Open Journal of soil Science* **4**: 469–493.

Kariaga, B. (2004). Intercropping maize with cowpeas and beans for soil and water management in western kenya, *Proceedings of the 13th international soil conservation organization conference*, pp. 1–5.

Keller, T., Sandin, M., Colombi, T., Horn, R. and Or, D. (2019). Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning, *Soil and Tillage Research* **194**: 104293.

Kiage, L. M. (2013). Perspectives on the assumed causes of land degradation in the rangelands of sub-saharan africa, *Progress in Physical Geography: Earth and Environment* .

Kibblewhite, M., Ritz, K. and Swift, M. (2008). Soil health in agricultural systems, *Philosophical Transactions of the Royal Society B: Biological Sciences* **363**(1492): 685–701.

Kimaro, J. (2019). A review on managing agroecosystems for improved water use efficiency in the face of changing climate in tanzania, *Advances in Meteorology* **2019**.

Kimaro, J. and Bogner, C. (2019). Water management under traditional farming systems: Practices and limitations of the mfongo system around mt. kilimanjaro.

Kimaro, J. G., Scharsich, V., Huwe, B. and Bogner, C. (2019). Distribution of traditional irrigation canals and their discharge dynamics at the southern slopes of mount kilimanjaro, *Frontiers in Environmental Science* **7**: 24.

Kimaro, J., Scharsich, V., Huwe, B. and Bogner, C. (2017). Linking hydrology of traditional irrigation canals and socio-economic aspects of agricultural water use around mt. kilimanjaro, *EGUGA* p. 15379.

Kitzinger, J. (1994). The methodology of focus groups: the importance of interaction between research participants, *Sociology of health & illness* **16**(1): 103–121.

Komakech, H., van Koppen, B., Mahoo, H. and van der Zaag, P. (2011). Pangani river basin over time and space: On the interface of local and basin level responses, *Agricultural Water Management* **98**(11): 1740–1751.

König, N., Blum, U., Symossek, F., Bussian, B., Ellinghaus, R., Furtmann, K., Gärtner, A., Gutwasser, F., Hauenstein, M. and Kiesling, G. (2005). Handbuch forstliche analytik, *Gessellschaft für Analytik. Bonn: Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft* .

Kuyah, S., Öborn, I. and Jonsson, M. (2017). Regulating ecosystem services delivered in agroforestry systems, *Agroforestry*, Springer, pp. 797–815.

Körner, C., Ohsawa, M., Spehn, E., Berge, E., Bugmann, H., Groombridge, B., Hamilton, L., Hofer, T., Ives, J., Jodha, N., Messerli, B., Pratt, J., Price, M., Reasoner, M., Rodgers, A., Thonell, J., Yoshino, M., Baron, J., Barry, R., Blais, J., Bradley, R., Hofstede, R., Kapos, V., Leavitt, P., Monson, R., Nagy, L., Schindler, D., Vinebrooke, R. and Watanabe, T. (2005). *Ecosystems and human well-being: current state and trends*, Vol. 1, Island Press, Washington, DC, USA, chapter Mountain Systems, pp. 681–716.

Lal, R. (2017). Soil erosion by wind and water: problems and prospects, *Soil erosion research methods*, Routledge, pp. 1–10.

Li, X., El Solh, M. and Siddique, K. (2019). *Mountain Agriculture: Opportunities for Harnessing Zero Hunger in Asia*, Food and Agriculture Organization of the United Nations (FAO).

Maghimbi, S. (2007). Recent changes in crop patterns in the kilimanjaro region of tanzania: the decline of coffee and the rise of maize and rice, *African study monographs* **35**: 73–83.

Maguire, R. O. and Sims, J. T. (2002). Measuring agronomic and environmental soil phosphorus saturation and predicting phosphorus leaching with mehlich 3, *Soil Science Society of America Journal* **66**(6): 2033–2039.

Martínez-Mena, M., Carrillo-López, E., Boix-Fayos, C., Almagro, M., Franco, N. G., Díaz-Pereira, E., Montoya, I. and De Vente, J. (2020). Long-term effectiveness of sustainable land management practices to control runoff, soil erosion, and nutrient loss and the role of rainfall intensity in mediterranean rainfed agroecosystems, *Catena* **187**: 104352.

Masmoudi, S., Magdich, S., Rigane, H., Medhioub, K., Rebai, A. and Ammar, E. (2020). Effects of compost and manure application rate on the soil physico-chemical layers properties and plant productivity, *Waste and Biomass Valorization* **11**(5): 1883–1894.

Muchane, M. N., Sileshi, G. W., Gripenberg, S., Jonsson, M., Pumariño, L. and Barrios, E. (2020). Agroforestry boosts soil health in the humid and sub-humid tropics: A meta-analysis, *Agriculture, Ecosystems & Environment* **295**: 106899.

Mwangi, H. M., Lariu, P., Julich, S., Patil, S. D., McDonald, M. A. and Feger, K.-H. (2018). Characterizing the intensity and dynamics of land-use change in the mara river basin, east africa, *Forests* **9**(1): 8.

Mwango, S. B., Msanya, B. M., Mtakwa, P. W., Kimaro, D. N., Deckers, J. and Poesen, J. (2016). Effectiveness of mulching under miraba in controlling soil erosion, fertility restoration and crop yield in the usambara mountains, tanzania, *Land Degradation & Development* **27**(4): 1266–1275.

Mwendera, E., Hazelton, D., Nkhuwa, D., Robinson, P., Tjijenda, K. and Chavula, G. (2003). Overcoming constraints to the implementation of water demand management in southern africa, *Physics and Chemistry of the Earth, parts A/B/C* **28**(20-27): 761–778.

Nahayo, A., Pan, G. and Joseph, S. (2016). Factors influencing the adoption of soil conservation techniques in northern rwanda, *Journal of Plant Nutrition and Soil Science* **179**(3): 367–375.

Nyangena, W. (2008). Social determinants of soil and water conservation in rural kenya, *Environment, Development and Sustainability* **10**(6): 745–767.

O'Kting'ati, A. and Kessy, J. (1991). The farming systems on mount kilimanjaro, *The Conservation of Mount Kilimanjaro. IUCN, Gland and Cambridge* pp. 71–80.

Palombi, L., Sessa, R. et al. (2013). Climate-smart agriculture: sourcebook., *Climate-smart agriculture: sourcebook.* .

Passioura, J. (2002). Soil conditions and plant growth, *Plant, Cell & Environment* **25**(2): 311–318.

Phengphaengsy, F. and Okudaira, H. (2008). Assessment of irrigation efficiencies and water productivity in paddy fields in the lower mekong river basin, *Paddy and Water Environment* **6**(1): 105–114.

Pilgrim, E. S., Osborne, J. and Winter, M. (2018). Evaluating the multiple benefits of multi-layered agroforestry systems.

Querné, A., Battie-laclau, P., Dufour, L., Wery, J. and Dupraz, C. (2017). Effects of walnut trees on biological nitrogen fixation and yield of intercropped alfalfa in a mediterranean agroforestry system, *European Journal of Agronomy* **84**: 35–46.

Ramakrishnan, P. (2005). Mountain biodiversity, land use dynamics and traditional ecological knowledge, *Global Change and Mountain Regions*, Springer, pp. 551–561.

Rashmi, I., Shirale, A., Kartikha, K., Shinogi, K., Meena, B. and Kala, S. (2017). Leaching of plant nutrients from agricultural lands, *Essential Plant Nutrients*, Springer, pp. 465–489.

Røhr, P. C. and Killingtveit, Å. (2003). Rainfall distribution on the slopes of mt kilimanjaro, *Hydrological sciences journal* **48**(1): 65–77.

Rust, N. A., Abrams, A., Challender, D. W., Chapron, G., Ghoddousi, A., Glikman, J. A., Gowan, C. H., Hughes, C., Rastogi, A., Said, A. et al. (2017). Quantity does not always mean quality: the importance of qualitative social science in conservation research, *Society & Natural Resources* **30**(10): 1304–1310.

Sahle, M. and Yeshitela, K. (2018). Dynamics of land use land cover and their drivers study for management of ecosystems in the socio-ecological landscape of gurage mountains, ethiopia, *Remote Sensing Applications: Society and Environment* **12**: 48–56.

Schreiner-McGraw, A. P. and Vivoni, E. R. (2018). On the sensitivity of hillslope runoff and channel transmission losses in arid piedmont slopes, *Water Resources Research* **54**(7): 4498–4518.

Sébastien, L. (2010). The chagga people and environmental changes on mount kilimanjaro: Lessons to learn, *Climate and Development* **2**(4): 364–377.

Shah, A. N., Tanveer, M., Shahzad, B., Yang, G., Fahad, S., Ali, S., Bukhari, M. A., Tung, S. A., Hafeez, A. and Souliyanonh, B. (2017). Soil compaction effects on soil health and cropproductivity: an overview, *Environmental Science and Pollution Research* **24**(11): 10056–10067.

Sharma, N., Singh, R. J., Mandal, D., Kumar, A., Alam, N. and Keesstra, S. (2017). Increasing farmer's income and reducing soil erosion using intercropping in rainfed maize-wheat rotation of himalaya, india, *Agriculture, ecosystems & environment* **247**: 43–53.

Shen, J. (1981). *Discharge characteristics of triangular-notch thin-plate weirs*, number 1617, United States Department of the Interior, Geological Survey.

Soini, E. (2005). Land use change patterns and livelihood dynamics on the slopes of Mt. Kilimanjaro, Tanzania, *Agricultural Systems* **85**(3): 306–323.

Sokile, C. S., Kashaigili, J. J. and Kadigi, R. M. (2003). Towards an integrated water resource management in tanzania: the role of appropriate institutional framework in rufiji basin, *Physics and Chemistry of the Earth, Parts A/B/C* **28**(20): 1015–1023.

Sokile, C. S., Mwaruvanda, W., Van Koppen, B. et al. (2005). Integrated water resource management in tanzania: Interface between formal and informal institutions, *conference African Water Laws: Plural Legislative Frameworks for Rural Water Management in Africa*, pp. 26–28.

Sun, F., Song, C., Wang, M., Lai, D. Y., Tariq, A., Zeng, F., Zhong, Q., Wang, F., Li, Z. and Peng, C. (2020). Long-term increase in rainfall decreases soil organic phosphorus decomposition in tropical forests, *Soil Biology and Biochemistry* **151**: 108056.

Suprayogo, D., van Noordwijk, M., Hairiah, K., Meilasari, N., Rabbani, A. L., Ishaq, R. M. and Widianto, W. (2020). Infiltration-friendly agroforestry land uses on volcanic slopes in the rejoso watershed, east java, indonesia, *Land* **9**(8): 240.

Tagseth, M. (2008). and the development of indigenous irrigation. methods and examples from kilimanjaro, tanzania., *Norsk Geografisk Tidsskrift - Norwegian Journal of Geograph* **14**(3).

Tengö, M., Brondizio, E. S., Elmqvist, T., Malmer, P. and Spierenburg, M. (2014). Connecting diverse knowledge systems for enhanced ecosystem governance: the multiple evidence base approach, *Ambio* **43**(5): 579–591.

Tilahun, A. and Teferie, B. (2015). Accuracy assessment of land use land cover classification using google earth, *American Journal of Environmental Protection* **4**(4): 193–198.

Tripathi, N. and Bhattarya, S. (2004). Integrating indigenous knowledge and gis for participatory natural resource management: State-of-the-practice, *The electronic journal of information systems in developing countries* **17**(1): 1–13.

Turkelboom, F., Poesen, J. and Trébuil, G. (2008). The multiple land degradation effects caused by land-use intensification in tropical steeplands: A catchment study from northern thailand, *Catena* **75**(1): 102–116.

Udom, B. E. and Ehilegbu, J. (2018). Critical moisture content, bulk density relationships and compaction of cultivated and uncultivated soils in the humid tropics, *Asian Soil Research Journal* pp. 1–9.

Vågen, T., Shepherd, K. D., Walsh, M. G., Winowiecki, L., Desta, L. T. and Tondoh, J. E. (2010). Afsis technical specifications: soil health surveillance, *Africa Soil Information Service (AfSIS). Nairobi, Kenya: World Agroforestry Centre* .

van Laak, M., Klingenberg, U., Peiter, E., Reitz, T., Zimmer, D. and Buczko, U. (2018). The equivalence of the calcium-acetate-lactate and double-lactate extraction methods to assess soil phosphorus fertility, *Journal of Plant Nutrition and Soil Science* **181**(5): 795–801.

Viviroli, D., Kummu, M., Meybeck, M., Kallio, M. and Wada, Y. (2020). Increasing dependence of lowland populations on mountain water resources, *Nature Sustainability* **3**(11): 917–928.

Woldesenbet, T. A., Elagib, N. A., Ribbe, L. and Heinrich, J. (2018). Catchment response to climate and land use changes in the upper blue nile sub-basins, ethiopia, *Science of the total environment* **644**: 193–206.

Zdravkovich, M. M. (1997). *Flow around Circular Cylinders: Volume 2: Applications*, Vol. 2, Oxford university press.

Zech, M., Hörold, C., Leiber-Sauheitl, K., Kühnel, A., Hemp, A. and Zech, W. (2014). Buried black soils on the slopes of Mt. Kilimanjaro as a regional carbon storage hotspot, *CATENA* **112**: 125–130.

Chapter 2

Distribution of traditional irrigation canals and their discharge dynamics at the southern slopes of Mount Kilimanjaro

Jerome G. Kimaro [1,2*], Valeska Scharsich [3], Andreas Kolb [1], Bernd Huwe [1] and Christina Bogner [3].
[1]Department of Soil Physics, University of Bayreuth, Bayreuth, Germany.
[2]Directorate of research, Tanzania Wildlife Research Institute, Tanzania. [3]Ecological Modeling, BayCEER, University of Bayreuth, Bayreuth, Germany.

Corresponding author: J. Kimaro. Email: jerome.kimaro@tawiri.or.tz

Short title: Traditional Irrigation Canals of Mt. Kilimanjaro

Published in Frontiers in Environmental Science. 2019 Mar 12;7:24.

Abstract

On the southern slopes of Mt. Kilimanjaro, like in many other regions in East Africa, agriculture strongly depends on irrigation. Water is supplied to farms by an extensive network of open unlined canals, most of them built centuries ago. However, information about the distribution of these irrigation canals and the dynamics of their discharge is rare, thus hampering the implementation of sustainable solutions for agricultural water management.

We suppose that several factors like topography, soil properties, shifts of cropping patterns, and weak institutions affect the availability and management of agricultural water. Therefore, in this study, we determined (i) the distribution of irrigation canals (ii) their discharge patterns, and (iii) constraints to their sustainable management. A mixed-method approach consisting of both quantitative and qualitative methodologies was used. The discharge of canals was measured at 11 locations along an altitudinal gradient and selected canals were mapped to understand their distribution, physical characteristics, and potential risks that limit their optimal discharge. Terrain attributes were derived from the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) Digital Elevation Model (DEM) image and soil properties were measured to understand permeability and stability of the soil. Additionally, we conducted focus group discussions with participants from 15 villages and 10 key informants interviews. We found that the discharge of canals increased with decreasing elevation. The median daily discharges equalled 12.6, 9.5, and 7.0 l/s in the lower, mid, and upper areas, respectively. During the dry season, the discharge of canals was higher than in the short rainy season. Landscape in the central part of the study area was the steepest ($slope > 60\%$) and the roughest ($TopographicRuggednessIndex > 80$ m). We attribute this to terrain heterogeneity across the landscape, thus community decisions about distribution and maintenance of canals could differ across different villages. Furthermore, current shifts in cropping patterns increased irrigation water demands. Both formal and informal water institutions were constrained with several challenges that affected the overall management of canals and their sources. The findings of this study could contribute to various efforts dedicated to improving the management of water resources around Mt. Kilimanjaro.

Keywords: *Traditional canals*, *water management*, *farming systems*, *Chaggas*, *agroforestry*, *terrain*, *Mt. Kilimanjaro.*

2.1 Introduction

Mountain ecosystems provide a range of supporting and provisioning ecosystem services, including food production. Over one billion people live in mountains, and many more depend on mountain resources and services (Körner, 2004). Thus, mountain ecosystems play an important role in sustaining human well-being. Food production strongly depends on availability of water. In East Africa, rainfall patterns exhibit a strong seasonality (Haile, 2005) and irrigation is essential for maintaining crop production during the dry season. Mt. Kilimanjaro is recognized as an important water tower in East Africa and is one of UNESCO's world heritage sites due to its high biodiversity (Hemp, 2006). The mountain is an important contributor to the Pangani River, a major river in north-eastern Tanzania (Røhr and Killingtveit, 2003).

Topography, soil properties and agricultural practices influence the supply and distribution of water in different ways. Run-off generation, for example, depends both on topography and soil moisture that is itself affected by soil physical and hydraulic properties (Beven et al., 1988). Changes in farming system like removal of indigenous trees and expansion of monoculture cropping can potentially decrease the water use efficiency within farms. Indeed, agroforestry practices could improve soil water storage (Udawatta et al., 2017; Kuyah et al., 2017). Additionally, annual high-value crops have been reported to replace perennial crops around Mt. Kilimanjaro, (Maghimbi, 2007) leading to a larger irrigation demand (Turpie et al., 2005). Therefore, the increased irrigation demand is likely to intensify competition for water among users. This can fuel social conflicts, especially between upstream and downstream users (Wiesmann et al., 2000; Amede, 2015).

Improving the link between local communities and public institutions can improve water management. However, experience from different parts of the country indicates that participation of local communities is still unsatisfactory (Dungumaro and Madulu, 2003). Often, their experience and expertise are ignored by planners and managers, which might negatively impact the management of water resources (Maganga, 1998, 2003). To promote participatory approaches in water management, donor communities have promoted the concept of Integrated water resources management (IWRM) in developing countries (Mehta and Movik, 2014). In Tanzania, water user associations (WUA) have been created in Pangani and Rufiji River basins, for example, to improve equitable water accessibility among user groups. However, there are several socio-economic barriers that limit the full implementation of WUA at the local level(Komakech et al., 2011; Sokile et al., 2003). Similar observations have been reported by (Biswas, 2008) who noted that traditional water management systems are still popular in developing countries despite the heavy promotion of IWRM by international institutions.

Around the southern slopes of Mt. Kilimanjaro, the open unlined canals (Mfongo in the local Chagga dialect) have been used by Chagga people, the ethnic group of Bantu origin, for decades. (Winter, 1994; Tagseth, 2008; Nakawuka et al., 2017) reported several drivers that influenced the establishment of canals around Mt. Kilimanjaro. Like other communities in EA, canals were important for sustaining agriculture food production and domestic uses (Winter, 1994; Dundas, 1924). Around Mt. Kilimanjaro, the increased diversity of food and cash crops in traditional Chagga home gardens was influenced by the presence of canals. Chagga dominated the supply of finger millet (Eleusine coracana) in ancient coastal caravan trade after expansion of irrigation canals around Mt. Kilimanjaro (Bender, 2008; Grove, 1993).

Nearly 80% of total mountain discharge is assumed to be consumed by smallholder farmers (Misana, 1991). However, information about the distribution of irrigation canals and the dynamics of their discharge is rare, thus hampering the implementation of sustainable solutions for agricultural water management. We suppose that hydrological patterns and management of irrigation canals at the southern slopes of Mt. Kilimanjaro are influenced by the complex interactions of several factors like topography, soil properties, shifts of cropping patterns, and weak institutions responsible for water management. In this study, we hypothesize that the mountain canal system is unevenly distributed, and its flow is not constant over time. Therefore, the aim of this study is to determine (i) the distribution of irrigation canals (ii) their discharge patterns, and (iii) constraints to their sustainable management. This information could contribute to improving the management of water resources at the southern slopes of Mt. Kilimanjaro.

2.2 Materials and Methods

2.2.1 Study area

Mt. Kilimanjaro is located 300 km south of the equator in Tanzania, on the border to Kenya, between 2°45′ and 3°25′S and 37°00′ and 37°43′E. This study was conducted on the southern slopes of Mt. Kilimanjaro starting from the plains (colline zone, 900 m) up to the forest (submontane zone, 1600 m) (Figure 2.1). Major land uses in this area are influenced by the altitudinal gradient. The lower area is dominated by maize monocropping and pastoralism (Misana et al., 2012; Soini, 2005). In the mid-area (1200 m–1350 m) the dominant farming systems are coffee–banana agroforestry and increasingly also maize fields. Additionally, several coffee estates operate as large-scale farming in the study area. In the upper area (1350–1600 m), Chagga home gardens, a traditional form of agroforestry with banana and coffee as dominant crops, have been cultivated for centuries by local inhabitants (Fernandes et al., 1985).

Two distinct rainy seasons occur in the study area; the long rains start from mid-March and stop at the end of May, while the short rains occur between October to December. Occasionally, short rains extend to the end of January of the coming year. The driest period is from July to the end of September, while April and May are the wettest months. The mean annual rainfall increases from 600–900 mm in the lower area, to 1000–1200 mm in the mid-area and 1800–2000 mm in the upper area, respectively (Hemp, 2005; Misana et al., 2012).

The soils at Mt. Kilimanjaro originate from volcanic material. Because their genesis is largely dominated by the altitudinal gradient, similar soils developed at similar altitudes. On the small and steep volcanic craters on the East of Mt. Kilimanjaro, the main soil type is Leptosol (IUSS Working Group WRB, 2015; Borrelli et al., 2017), whereas in the plains Acrisols, Ferralsols, Lixisols, Nitisols and Vertisols dominate (Zech et al., 2014).

The open canals dug into the earth (*Mfongo* in Chagga dialect) are still the major infrastructure for conveying agricultural water through gravity to crop fields around Mt. Kilimanjaro. Canals obtain their water both from rivers and springs, most of them confined within the montane forest belt. However, a number of springs are found around the upper cultivated areas. In addition to canals, the Chagga irrigation system is composed of small earth dams, 30 – 50 m^2 in size, locally known as *Nduwas*(online Supplementary Figure S1).

Chaggas used *Nduwas* to sustain irrigation during the dry season or where the sources have a low discharge capacity. Because most *Nduwas* are situated inside the national park with restricted access, they are not well managed (Pers.comm.). When a canal is not used for irrigation, especially during the rainy season or night, water is drained to the river through a secondary canal at the end of the scheme.

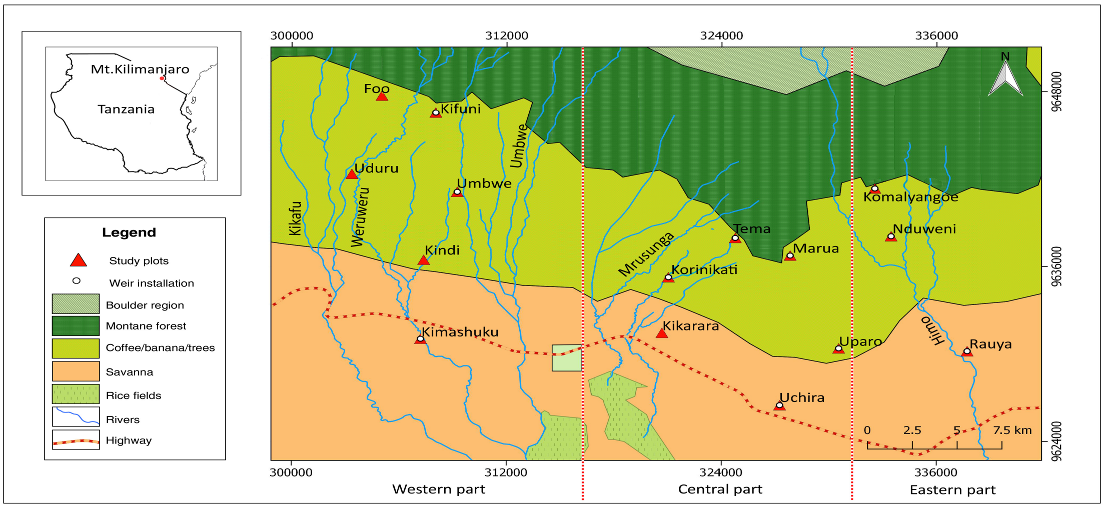

Figure 2.1: Study area. We subdivided it into the western, central and eastern parts to simplify the description of results.

2.2.2 Mapping of the canal network

The Canal network extends over a vast area with variable geomorphology attributes and land uses (Devenne, 2006; Misana et al., 2012). For comparison purposes, the study area was subdivided into three subregions across the slope, namely: western, central, and eastern parts respectively. In the western part of the study area, mapping covered Kifuni, Uduru and Kimashuku villages. Additionally, we mapped canals located in Tema, Korinikati and Kikarara villages around the central part. Villagers familiar with the management of canals in their villages helped to locate the canals, identify their names, sources, and locations. We used a GPS device (Garmin GPSMAP 64s) to mark the course and intake points of primary canals. Additionally, we measured physical features like width, depth, length, and intersection angles using a ruler and an angle protractor. Depth and width of canals were measured at several points ($N = 50$) for each surveyed canal. Notably, mapping secondary and tertiary canals were not possible because they were too numerous. However, we established a hand-drawn sketch map as an expression of the actual layout we observed in the field.

Additionally, to canals, we also assessed the structure and functions of earth dug reservoirs, which are an important part of the Chagga irrigation system. We measured their physical features like width, depth, and length. Besides that, traditional techniques employed in their construction and maintenance were assessed. Further to this, we evaluated the major risk factors related to damage to canals infrastructure and water losses during conveyance. Finally, recorded coordinates were imported into a GIS environment to produce a distribution map of canals. QGIS Desktop 2.14.15 program inbuilt tools were used to compute spatial features like canal length and distances between canals. The same program was used to produce canals distribution maps.

2.2.3 Terrain analysis

Topography influences hydrological processes and affects stream network, soil moisture, and groundwater flow (Beven et al., 1988). Therefore, topographical indices can be used to understand the distribution of canals and their discharge patterns. Digital Elevation Model (DEM) satellite image with the 30 m resolution was downloaded from the Earth Explorer, USGS website (`https://earthexplorer.usgs.gov`). QGIS version 2.14 and GRASS version 7.0 were used for subsequent GIS analyses. Prior to the analysis, surface depressions of the DEM were filled (Wang and Liu, 2006). For the terrain analysis, we used r.watershed and r.slope.aspect modules from the GRASS GIS tool kit for Hortonian analysis (Jasiewicz and Metz, 2011; Martz and Garbrecht, 1993). The module r.watershed was used to compute Topographic Wetness Index (TWI) and the drainage direction (Dd) based on single direction D8 flow model (O'Callaghan and Mark, 1984). Furthermore, the QGIS raster terrain analysis plugin was used to compute terrain slope and Ruggedness Index (TRI).

The TWI (Beven and Kirkby, 1979) indicates the relative soil moisture at a point and shows where the flow accumulates:

$$\mathrm{TWI} = \ln\left(\frac{a}{\tan\beta}\right), \tag{2.1}$$

where a is the upstream contributing area, and β the slope, respectively.

The TRI describes topographic heterogeneity (Riley, 1999) and is calculated as

$$\mathrm{TRI} = \left[\sum (x_{ij} - x_{00})^2\right]^{\frac{1}{2}} \tag{2.2}$$

where (x_{00}) is the elevation of a pixel in the DEM and (x_{ij}) are elevations of its eight adjacent pixels.

2.2.4 Soil physical and hydraulic properties

To understand the susceptibility of the unlined canals to percolation losses, we measured the saturated soil hydraulic conductivity (K_{sat}). Jadczyszyn and Niedźwiecki (2005) and Wachyan and Rushton (1987) reported that values of saturated soil hydraulic conductivity can be used to predict soil and water loss under different land management practices and climatic conditions. In lower areas measurements were conducted in Kimashuku, Kikarara, Uchira and Rauya, while mid-areas involved Uduru, Korinikati, Uparo and Nduweni villages and upper areas Foo, Tema, Komalyangoe and Marua.

In each village, we established four subplots in a 1 ha plot based on the Land Degradation Surveillance Framework (LDSF) (Vågen et al., 2010). Because the canals are unlined and shallow (15–30 cm) and frequently scrapped during cleaning, we assumed that their permeability was similar to the soil on adjacent farms. We measured K_{sat} with a double ring infiltrometer (Köhne et al., 2011).

Soil samples for texture analysis were collected from the same subplots. Bulk soil samples were collected from a depth of 30 cm. Samples were air-dried and sieved <2 mm. Organic matter was removed by hydrogen peroxide in the hot bath. Wet sieving using a series of sieves was used to obtain sand classes and the fine particle suspension (Carter, 1993). Finally, the proportions of clay, silt, and fine sand were determined by automated sedimentation analysis using PARIO equipment (METER Environment Ltd, USA) (Durner et al., 2017).

2.2.5 Discharge measurements

To determine the discharge of canals, a network of eleven 60° V-notch weirs was established at selected locations. We used the concept of citizens' science (Brossard et al., 2005) and developed a protocol in which 11 villagers were trained to read the weirs, monitor and report various causes of discharge fluctuations in canals. Discharge was recorded three times a day (morning, afternoon, and evening) from June 2015 to Feb 2016, after the end of the long rainy season (from March to June). Most inflows of canals were either closed or the flow rate was reduced during the long rainy season because the irrigation demand decreases. Closing canals reduce the flooding risk caused by canal overflow.

Furrow discharge was computed by Kindsvater-Shen equation (Shen, 1981)

$$Q = 4.28 \cdot C \cdot \tan\left(\frac{\theta}{2}\right) \cdot (h+k)^{5/2}\,, \tag{2.3}$$

$$C = 0.607165052 - 0.000874466963 \cdot \theta + 6.10393334 \times 10^{-4} \cdot \theta^2 \tag{2.4}$$

$$k(f) = 0.0144902648 - 0.00033955535 \cdot \theta + 3.29819003 \times 10^{-6} \cdot \theta^2 - 1.06215442 \times 10^{-8} \cdot \theta^3 \tag{2.5}$$

where C is the discharge coefficient, h the height of water in the canal, k the head correction factor and θ the notch angle, respectively.

To determine the current status of canals, we asked members of village water committees to conduct a survey in their respective villages and to report on (i) the total number of present canals, (ii) their flow status (dried, perennial or seasonal) and (iii) their major sources.

2.2.6 Collecting socio-economic data through interviews

We organized Focus Group Discussions (FGDs) and key informants (KI) interviews to collect socio-economic information. The former involved 15 discussion meetings in villages where study plots were located. Between 10 and 15 villagers attended each meeting. The meetings involved diverse social groups of villagers like women, elderly people and leaders in order to obtain a good representation of their communities (Kitzinger, 1994). Before starting each meeting, the informed-consent procedure was followed to ensure the participants about the confidentiality of their identities and their contributions (Krueger and Casey, 2014).

Two major participatory approaches were used. Firstly, the open-ended protocol was used to guide discussions and secondarily, villagers formed discussion groups for brainstorming on different topics provided (Krueger and Casey, 2014). The following questions lead discussions: (i) Distribution of canals and their sources on mountain slope (ii)Procedures used in water sharing among key water users (iii) Major constraints to daily maintenance of canals and their sources (iv)Agricultural water management under different farming systems (v)Recent changes in cropping systems and agronomic practices (vi) Major causes of water losses during water conveyance in canals vii) Local perceptions about use of canals among Chagga people

Interviews with KI (10 interviews) involved the officials from Hai and Moshi Rural district councils, water experts from Pangani Basin Water Office in Moshi and officials from Northern Zone Irrigation Office. Our discussions broadly focused on institutional matters related to management of agricultural water, implications of changing farming systems and disturbances around Mt. Kilimanjaro.The following were major discussion questions: (i) Status of social linkages between traditional and formal institutions involved in water management (ii)Major anthropogenic disturbances threatening discharge of canals and their sources (iii) Compliance of national policies to sustainability of traditional canals (iv) Strategies to reduce water losses in canals and social conflicts among different user groups

2.2.7 Data analysis

To extract information from village water committee members, FGDs and KIs, several participatory approaches were used. Both qualitative and quantitative methods were used to generate contextualized data that can be counted, ranked and compared Ager et al. (2011). Farmers' observations regarding fluctuations of discharge in canals were grouped according to major causes, namely, normal flow (NRM), irrigation schedule (IS), repair and maintenance (RM), uncleared canals (UC), dried canal (DC) and other (OT), if farmers were uncertain about the actual cause of fluctuation. Findings from village committees about the status of irrigation canals within their villages were grouped into three classes based on annual flow regime patterns, namely perennial, seasonal and dried. The total number of canals in each village was calculated. Analysis of quantitative variables employed R-statistical program to generate descriptive statistics like frequency distribution (in percentage). Conversely, qualitative information from interviews was extracted by content analysis in order to categorize verbal data for classification and summarization (Hennink, 2013). All communication and discussion were in Kiswahili and translated in English later.

The discharge measurements are time series, and their temporal autocorrelation must be accounted for in a model. Thus, we used a Generalized Additive Model (GAM) that can handle time series (Hastie and Tibshirani, 1990). A GAM is a non-linear additive model that allows for classical fixed effects (as in an ANOVA) and can also describe the relationship between a predictor and the response variable as a smooth function. We fitted different smoothing functions of time per elevation. They represent a general temporal dynamic of the discharge. Furthermore, we included a random effect of village (i.e., a random difference of mean discharge between villages). Additionally, we assumed that discharge is a function of elevation and farmers' observations regarding fluctuations of discharge. The latter factor means that canal management has an influence on discharge. Both elevation and responses were included as fixed factors in the model:

$$y = s(\text{time}) + \beta_{\text{E}} + \beta_{\text{FO}} + b_{\text{V}} + \varepsilon\,, \tag{2.6}$$

where y is the discharge, $s(\text{time})$ the smooth term of time, β_{E}, β_{FO} are the fixed effects of elevation and farmers' observations (normal flow (NRM), irrigation schedule (IS), repair and maintenance (RM), uncleared canals (UC), dried canal (DC) and other (OT)), b_{V} is the random effect of the village and ε the error term, respectively. Observations with the status DC were excluded from the model. All calculations were done in R (R Core Team, 2018).

2.3 Results

2.3.1 Distribution of canals

Canal metrics like length, geographical orientation and physical locations of their intakes and routes indicate remarkable differences. Indeed, canals in lower areas were wider (median: 45 cm) compared to those in upper areas (median: 20 cm). Canals around the central part were longer compared to those around the eastern part. For example, Machombo and Mzuki canals were more than 7 km long within the cultivation area. However, we could not establish their actual lengths since their sources are located inside the forest (above 2000 m.a.s.l). By contrast, canals around the western part were not longer than 1.2 km. However, some canals were combined in order to extend their length. For example, the combination of Mrema (1.14 km) and Mwaana canals (1.3 km) around 1300 m.a.s.l, could be extended 2.5 km further downslope, around 1200 m.a.s.l (Figure 2.3). Additionally, several secondary and tertiary canals were branched from

Figure 2.2: Traditional irrigation canals around Mt.Kilimanjaro.

primary canals at an angle between $30-90$ degrees to convey water to irrigation schemes and individual plots (online Supplementary Figure S2).

Since there are numerous canals around Mt. Kilimanjaro, it was not possible to determine their total number, their drainage status and their physical features in each irrigation scheme. However, responses from FGDs and water experts from PWBO indicated that the canal network around the upper western and eastern parts could be denser than in the central part. However, because irrigation is increasing at lower slopes, there could be more tertiary canals compared to upper slopes. Nearly each farm plot was crossed by a tertiary canal conveying water to adjacent plots. KIs reported that between 1000 and 2000 primary irrigation canals were estimated to exist around the southern slopes of Mt. Kilimanjaro.

On the other hand, mountain geomorphology has an influence on the routing and orientation of canals (Figure 2.3). Since Chagga canals are gravity controlled, their flow is determined by landscape topography. The analysis of the drainage direction of the study area indicated different flow directions, which could also influence canal routing (online Supplementary Figure S3). Canals originating from western and eastern upper areas were flowing towards the south-east, while those from the central part were oriented towards the south-west. Additionally, the landscape around the central part was rougher. The median TRI values equalled 6.31, 4.5 and 2.8 m for the central, western and eastern parts, respectively (Figure 2.4).

Accordingly, steeper slopes ($median > 15\%$) were observed on farms around the

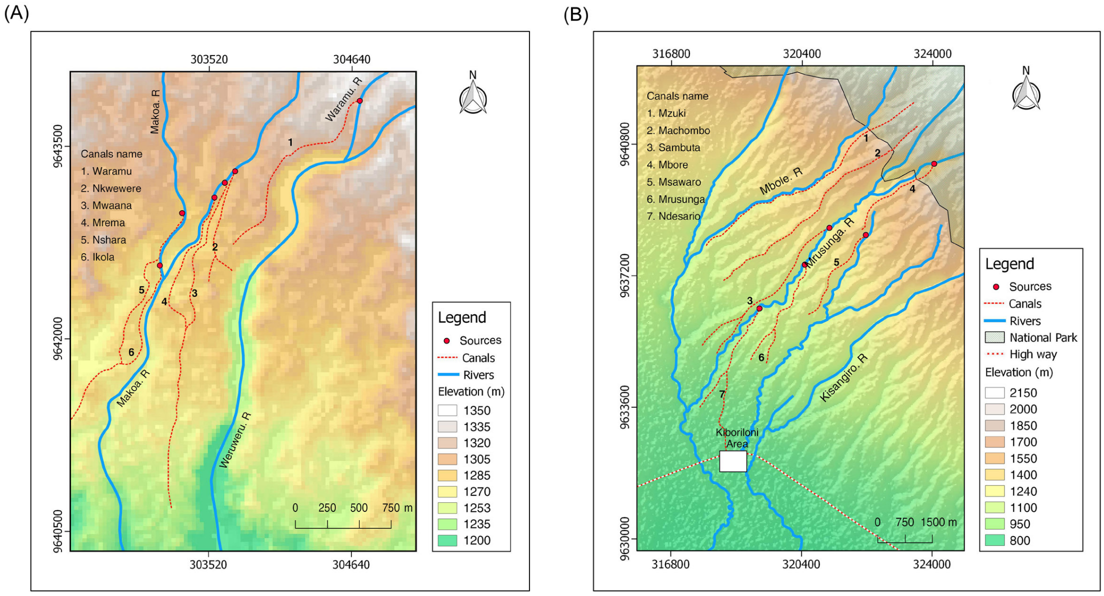

Figure 2.3: Distribution of canals around Uduru Village, western side of Mt. Kilimanjaro (A) and around central area of Mt. Kilimanjaro (B).

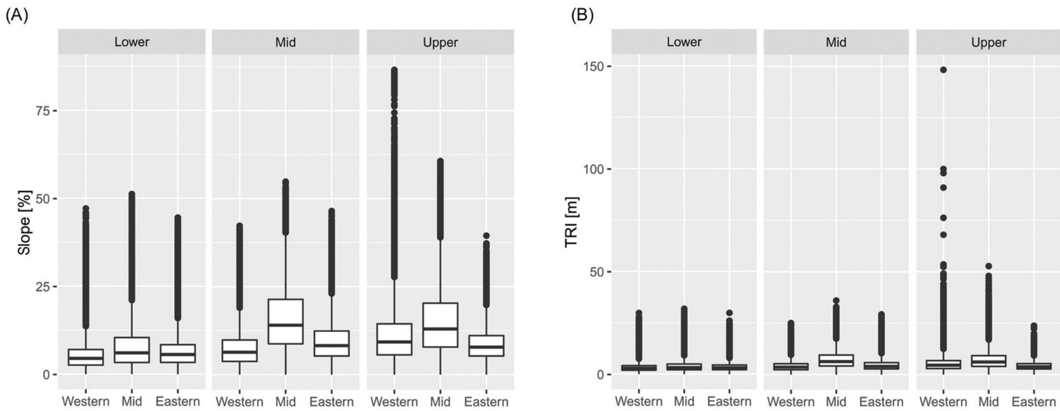

Figure 2.4: The variation of terrain slope around the southern slopes (A) and TRI of Mt. Kilimanjaro (B).

central part compared to those in the western and eastern parts (*median* $< 10\%$) (Figure 2.4). We observed a remarkable number of farms with slopes larger than 50% around Kidia and Mbokomu wards in the central part. However, a few cases of extreme steepness (*slope* $> 60\%$) were found on the upper slopes of the western part, like in Foo and Nkwarungo villages.

Table 2.1: Particle size distribution of the soil fine fraction and the percentage of soil organic matter (OM) Number arrange e.g. minima and maxima). The proportion of OM is based on the original dry weight of a sample, the proportions of sand, silt and clay on the weight after the destruction of organic matter.

Elevation	Village	Sand (%)	Silt (%)	Clay (%)	OM (%)
Lower	Kikarara	7–12	25–38	52–63	8–10
	Kimashuku[1]	8–9	19–22	69–73	24–24
	Rauya	4–4	15–50	46–81	11–14
	Uchira	9–13	27–77	10–64	3–13
Mid	Korinikati	4–6	36–63	32–60	13–24
	Nduweni	15–28	32–45	31–51	19–22
	Uduru[1]	26–40	42–52	18–22	30–33
	Uparo	14–20	18–48	35–68	9–12
Upper	Foo[1]	48–66	28–46	6–6	40–43
	Komalyangoe	42–48	11–31	26–42	44–52
	Marua	35–46	13–19	36–48	14–18
	Tema	24–29	11–27	47–60	15–18

The TWI around the lower areas was slightly higher ($median > 6\ m$) compared to mid and upper slopes ($median < 6m$). The combined effect of high TWI and low slope could provide favorable conditions for the gravity-based types of irrigation, like Chagga traditional canals. Although Chagga farmers cannot quantify water needs for different crops, a number of traditional techniques have already been developed. For example, farmers use a hand how to control water accumulation around crop root zone during irrigation, old banana stems or stones to regulate the speed of water within canals, or divert excessive canal flow back to the river course.

2.3.2 Physical and hydraulic soil properties

The particle size distribution (soil texture) varied along the elevation (Table 2.1). Generally, the content of sand and organic matter increased, while the content of clay decreased with increasing elevation. The soil texture also varied between villages in the same elevation zone. For example, the largest proportion of sand (48–66%) was measured in Foo compared to Tema (24–29 %). Accordingly, soil hydraulic conductivity K_{sat} increased with increasing elevation as the soils became more sandy, from 1.1 to 4.9 cm/hr (Figure 2.5).

2.3.3 Discharge patterns of canals

The discharge of canals increased with decreasing elevation (Figure 2.6). The median daily discharges equalled 12.6, 9.5 and 7.0 l/s in the lower, mid and upper areas, respectively. It also varied across villages in the same elevation zone. For example, in the

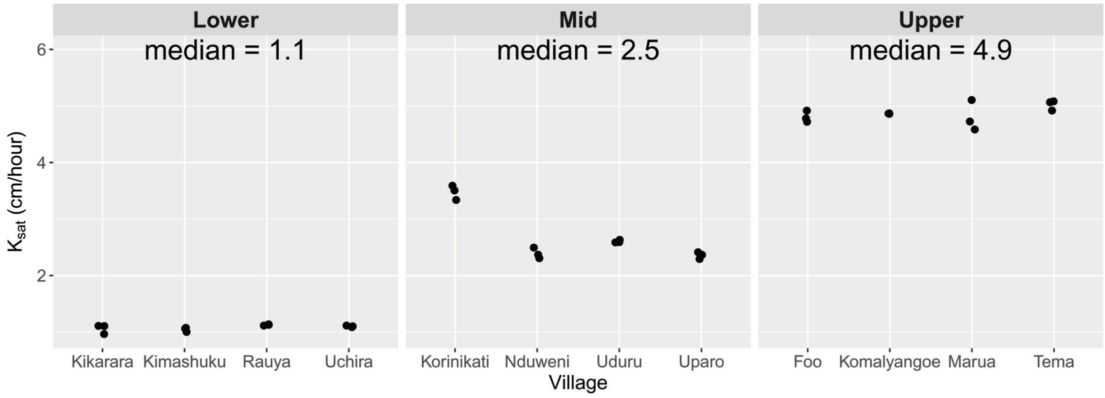

Figure 2.5: Spatial distribution of hydraulic conductivity around southern slopes of Mt. Kilimanjaro.

lower area, canals in Uchira were dry during the whole observation period, while those in Kimashuku and Rauya conducted water. Similarly, in the upper area, the value of median discharge in Kifuni was nearly 50% larger than in Tema. The participants of FGDs and KI informants reported that most canals around Mt. Kilimanjaro were not lined. Given that soil permeability is heterogeneous (Figure 2.5), percolation losses probably vary across the landscape.

We recorded higher discharge during the dry (July to end of October) compared to the short rainy season (November to end of January) (Figure 2.7). The irrigation demand decreases during the rainy season and the flow is reduced to prevent flooding. However, a certain minimum level of discharge is maintained during the rainy season to serve water for domestic use and livestock (Pers.comm).

The modelling results are summarized in Table 2.2, additional information on the distribution of residuals and significance of smooth and random terms can be found in the online supplementary material. The parameter β_{E}: Lower is the discharge in the lower area when farmers reported normal flow (NRM) and all other factors are additive to this model intercept. The discharge decreases significantly with increasing elevation. However, the difference between the mid and the upper areas is not significant (Wald test, $p = 0.228$). Irrigation schedule (IS) and repair and maintenance (RM) decrease the discharge significantly, as do uncleaned canals (UC) and other causes not specified by the farmers (OT). Interestingly, uncleaned canals and irrigation reduced the discharge by roughly the same amount.

2.3.4 Canal management

Water governance around Mt. Kilimanjaro is under both traditional and formal institutions. The former involves village or community water committees, while the latter consists of Hai and Rural Moshi District authorities. KIs responses from both districts indicated some common perceptions related to challenges of canal water management.

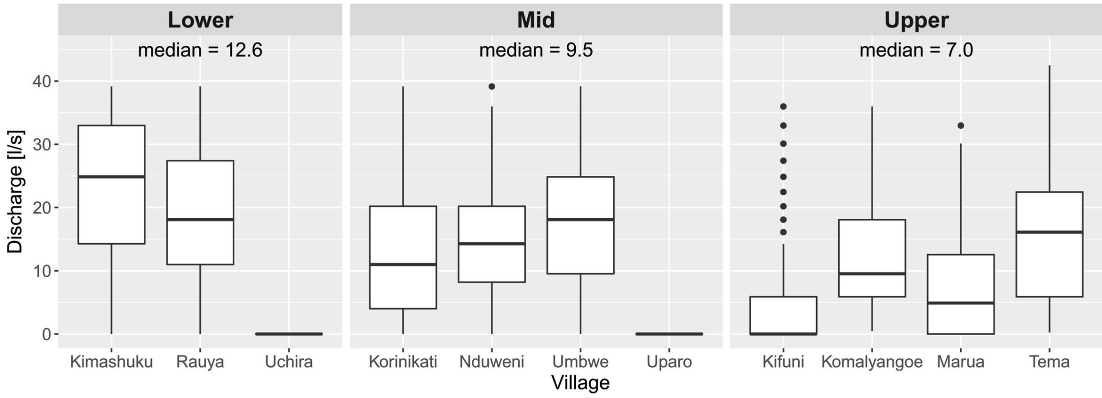

Figure 2.6: Spatial variability of discharge in irrigation canals along the three elevation zones.

Table 2.2: Summary of the modelling results for the fixed and the interaction effects.

Parameter	Estimate	Std. error	t value	p value
β_{E}: Lower	25.58	0.71	35.98	< 0.001
β_{E}: Mid	-3.92	0.92	-4.28	< 0.001
β_{E}: Upper	-4.85	0.88	-5.55	< 0.001
β_{FO}: IS	-16.89	0.26	-63.80	< 0.001
β_{FO}: RM	-15.23	0.31	-48.82	< 0.001
β_{FO}: UC	-16.00	0.55	-29.03	< 0.001
β_{FO}: OT	-14.37	0.18	-81.04	< 0.001

The lack of sufficient funds was reported to limit several daily operations, like hiring more technical staff and paying for field transport. Land degradation was reported as the major environmental problem around Mt. Kilimanjaro. Several traditional techniques for land management, like long fallows, terraces, and mulching, are familiar to Chaggas. Nonetheless, they are less practised nowadays. Additionally, prohibited activities like cultivation or logging around water sources were reported to increase, thus water managers fear decreasing discharge of rivers and springs in the future.

Generally, authorities recognized the importance of canal irrigation to the livelihood of mountain communities. However, they are also concerned with non-agricultural user communities. Access of irrigation water was only restricted to the use of gravity-free canals whereas all conversional means for water abstraction, like the use of motorized pumps, have been strictly banned. Additionally, the expansion of gravity pipe water was mentioned as a priority. Enabling rural and peri-urban households to access clean domestic water is a national call. It was further mentioned that the national water policy has a number of weaknesses that limit the improvement of traditional irrigation schemes. The policy has prioritized the promotion of medium and large-scale commercial irrigation schemes and less emphasis on traditional subsistence schemes. Likewise, no clear

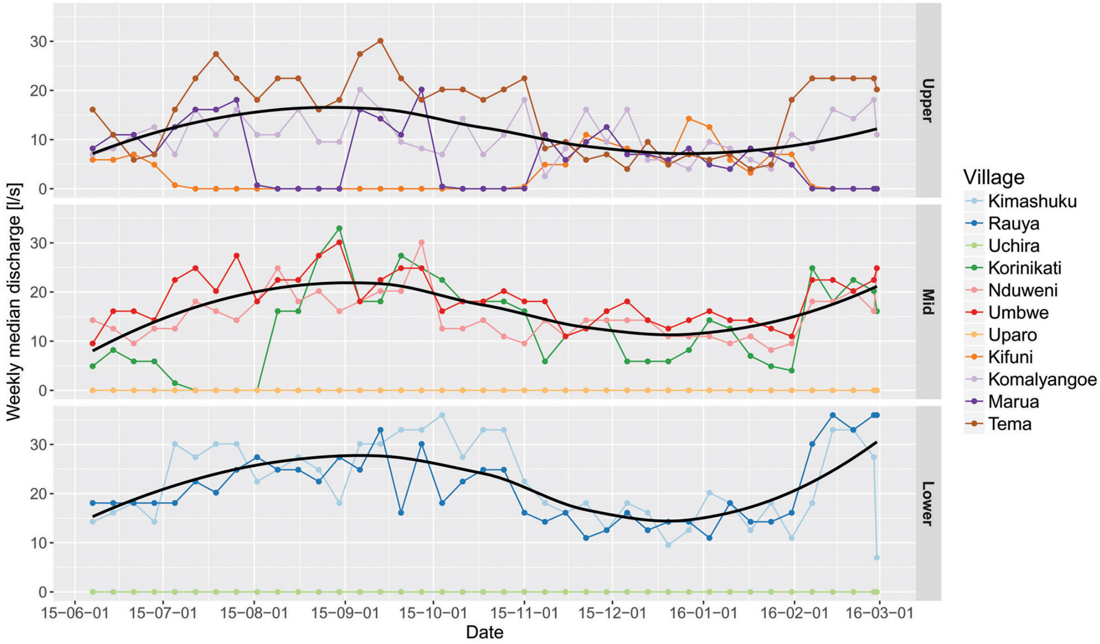

Figure 2.7: Dynamics of weekly discharge in irrigation canals along the three elevation zones. Black lines are produced by a loess smoother for visualization only. Discharge with the state DC (dry canal) was excluded from smoothing.

guidelines have been formulated for the implementation of integrated water resources management (IWRM) practices. Around Mt. Kilimanjaro, some recommendations of water user associations (WUA) were negatively perceived by local people. For example, villagers feared the introduction of user rights and fees for canal water use.

At the community level, the authority of traditional leaders has declined, hence fail to mobilize the voluntary force deployed for regular canal maintenance. Additionally, the trend of rural-urban migration among youths was reported to rise, leading to an increased proportion of elderly and children in the community who cannot undertake canal works. From FGDs meeting, we learnt that canal discharge has been decreasing over time based on responses (80%) of elderly participants whose age was above 50 years. However, the overall perceptions of canal management differed from one village to another. 70% of respondents from lower central part complained about lacking access to irrigation during the dry season. This was due to drying of canals before reaching lower areas. Likewise, nearly 100% of participants from Uparo and Uchira villages had a concern about the complete drying of their canals. Most villagers (68%) from upper areas were less concerned about scarcity of irrigation water. There is less irrigation around many villages in upper areas. However, an exception was noted in Kifuni and Marua villages, whereby 75% of participants were concerned about intermittent discharge of their canals. Notably, a substantial number of farmers from these villages were reported to grow hybrid coffee varieties that are less drought tolerant. Conversely, canals and their sources were used for different cultural purpose by Chagga. This includes ritual practices and paying tributes to ancestors who built them. We noted that most primary canals carried a name of their founder.

Farmers' commitment to canal management around Mt. Kilimanjaro is highly variable (Figure 2.8). Canals around the lower areas were better maintained. Indeed, farmers reported that canals in the upper areas were not regularly cleaned (UC) and the structures were not repaired frequently (RM). Consequently, a number of canals like Kifuni and Marua failed to maintain their discharge (DC) throughout the year. Notably, their case was different to that of Uparo and Uchira canals, which were affected by over-abstraction of their sources (Pers.comm). Additionally, different other factors (OT), like trampling over canal wall by human or animal, water theft, canal blockage by fallen tree or perforation of canal wall by stream crabs were reported to affected canal discharge, especially around upper areas.

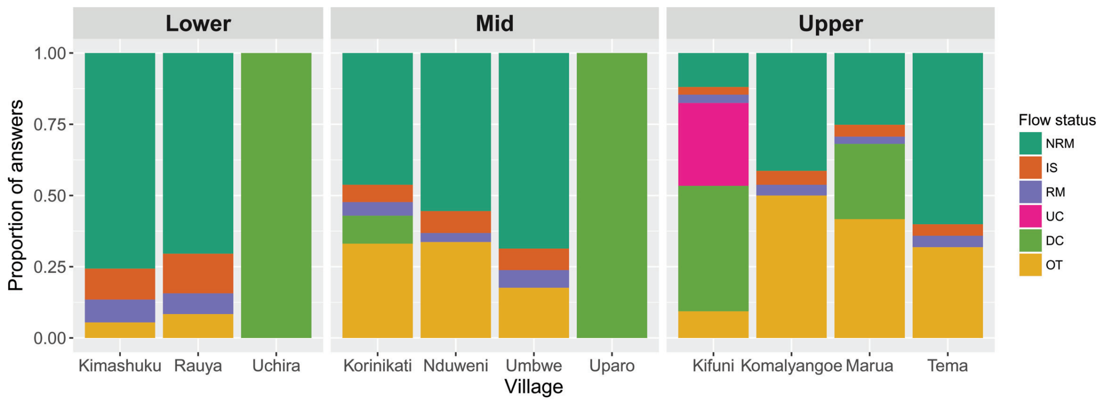

Figure 2.8: Farmers' observations on fluctuations of discharge in canals along the three elevation zones.

The assessment of the current status of irrigation canals from the selected ten villages indicated that most of the currently operating irrigation canals were perennial (47.7%) followed by seasonal (36.9%) while the least were dried canals (21.5%). It was difficult to quantify the status of reservoirs (*Nduwas*) since most of them were inside the national park.

Contrary to institutional matters, environmental factors also affected canal conveyance. Perforations of canal banks by stream crabs were common in the upper areas. Other biological activities along canals were rodents and termites channels. Furthermore, canals were susceptible to erosion, especially around the central area where canals run along steep slopes. When it rains, most canals were covered with transported sediments from upper slopes. Additionally, a few incidences of landslips were observed within the canal network. Sections of canals have been lost, leading to discontinuous flow.

2.4 Discussion

2.4.1 Distribution of canals

Because the irrigation system around Mt. Kilimanjaro is driven by gravity, distribution of canals could only favour water supply to some villagers. We attribute this to terrain topography, which affect routing and length of canals. This accords with Horton (1945) and Beven et al. (1988) who noted that landscape morphology affected the routing of the surface run-off through channels.

Among the three subregions of Mt. Kilimanjaro, the distribution of irrigation canals could be less dense around the central part where crop fields are found on hills, in valleys or along steep slopes. This topography limits the development of secondary canals towards locations where the terrain is not appropriate for gravity flow. Therefore, a considerable number of farm households could be confronted with both physical and economic water scarcity. Farmers on hills could be relying more on rain-fed agriculture. A previous study by Tagseth (2008) observed that rivers were already in deep gorges when crossing villages around Mbokomu in the central part. Similarly, Devenne (2006) noted that many canals in the central part run a long distance from their sources before reaching villages. During our field visit, villagers from villages around the lower central part, like Kiboriloni and Kikarara complained about shortage of irrigation water during the dry season.

By contrast, farmers around the western and eastern parts could easily access irrigation water. Lower terrain ruggedness is favourable to the establishment of canal intakes at multiple points along the river. An extensive irrigation network around Uduru and Kimashuku villages have favoured a successful horticultural production on the lower areas of Machame ward.

Although the use of simple motorized pumps could overcome terrain challenges, this is not an option around Mt. Kilimanjaro due to government restrictions on pumping water from rivers. Therefore, emphasize should be given to improving the traditional water harvesting techniques (*Nduwas*) which could solve water supply challenges in many villages where small streams are not used for irrigation because of their lower discharge rates. Nduwas have been an integral part of the irrigation systems around Mt. Kilimanjaro for decades.

Chagga customary systems have a direct link to the distribution of canals around Mt. Kilimanjaro, thus reorganizing their layout in order to improve water distribution could be difficult. A strong connection exists between water, spiritual beliefs and fortunes. For example, irrigation has been associated with successful settling of the first Chaggas on the slopes of Mt. Kilimanjaro (Grove, 1993; Winter, 1994). Furthermore, canals have been used for political re-establishment and gaining social status among local leaders (Bender, 2008; Homewood, 2006). Our findings are in agreement with other studies done in Africa whereby culture, rituals and beliefs have been connected to utilization of natural resources (Boaten, 1998). Thus, Chaggas' decision to maintain locations and names of their canals could be done deliberately for cultural reasons. Most canals were established before the Iron Age (Dundas, 1924), the pre-enlightenment era when working tools and state of technology were still underdeveloped in most part of Africa.

2.4.2 Discharge of irrigation canals

Chagga irrigation canals are very sensitive to a range of natural and human-induced factors which affect its water conveyance efficiency and ultimately the overall distribution of agricultural water. For example, steeper areas increased the water velocity in canals while in lower areas water accumulates due to a higher TWI value (Beven et al., 1988). Likewise, Strahler (1957) noted that landscape morphology influenced stream hydrographs, thus inducing spatial heterogeneity of catchment drainage. Given that most irrigation canals around Mt. Kilimanjaro are unlined, a considerable amount of water could be lost en route through percolation and evaporation. Additionally, raised earthen canal banks could allow lateral seepage, especially when canal flow is above ground level. Comparable studies have reported weakness of traditional irrigation canals. Assessment by FAO's has indicated a huge difference on field application efficiency between unlined earthed canals (<60%) compared to concrete line canals (<90%) (Brouwer et al., 1989). Likewise, Turpie et al. (2005), reported that irrigation canals around Mt. Kilimanjaro had a low efficiency, ranging between 15 and 50%.

Maintaining steady flow in traditional canals could be a challenging task to both farmers and water managers, in particular in areas with permeable soils. For example, high values of soil hydraulic conductivity and large proportion of sand in soils at the upper areas could lead to higher infiltration rates compared to lower areas. Water losses in canals have been reported as one of the major limitations to effectiveness of community-driven small holder traditional irrigation schemes in East Africa (Aberra, 2004; Ngigi et al., 2005; Makurira et al., 2007).

In contrast to traditional canals, establishment of modern canals consider several prerequisites that improves water use efficiency. These include the discharge capacity of the sources, topography, number of users, soil properties, type of crops grown and climate (Bos and Nugteren, 1990). Additionally, the control of canal flow can be easily manipulated within modern canals, even where terrain slope could limit desirable discharge rates for irrigation (Clemmens and Replogle, 1980).

Furthermore, we relate canal discharge patterns to agricultural water demands around Mt. Kilimanjaro. Along the slope, zonation of farming systems is very clear (Fernandes et al., 1985). Although maize monocropping is still dominant at lower areas (Misana et al., 2012), rice irrigation schemes at Lower Moshi, Mabogini and Njoro depend on mountain discharge (Ikegami, 1994). In upper areas, home gardens are still dominant and demand less irrigation. Agroforestry practice is known to improve soil water storage compared to annual crops mono-cropping (Udawatta et al., 2017; Kuyah et al., 2017). The exception is noted where vegetables are currently grown. Conversion of home gardens to vegetable and maize farming is increasing in upper areas of Mt. Kilimanjaro (Misana et al., 2012; Maghimbi, 2007).

Furthermore, the spatial variability of discharge could be related to current shifts of cropping patterns. According to the agricultural officer from Hai district (Pers.com), farmers increasingly prefer some new crop types, in particular vegetables and hybrid maize, due to their high market demands. Concurrently, several traditional crops were widely abandoned. The most affected ones include *Elfairia pedata* and *Dioscoreaceae family*. Agronomically, new crop varieties demands more irrigation water compared to traditional ones. This may influence changes on irrigation schedules and amount of irrigation water needed by some farmers.

2.4.3 Management challenges of traditional canals

Both formal and informal water institutions influence the current water management around Mt. Kilimanjaro. At the community level, declining authority of village water committees has been observed for decades. In the early 1960s, the government abolished all traditional rule systems in Tanzania and centralized the management of natural resources under the state (Kangalawe et al., 2014). Therefore, most of Chagga customary laws that enforce participation in canal works and protection of catchment resources became less respected by community members. On the other hand, the overall water management around Mt. Kilimanjaro indicates a top-down approach. According to Tagseth (2008); Cleaver and Toner (2006), equality balance is lacking between local community and state agencies on decision-making and representation in water projects development. Local communities have accumulated experience about hydrological behaviour of the catchment. Thus, integrating their local expertise could help to avoid unforeseen negative consequences of water projects at local level. Decisions made by one side could be a contravention to another priorities and hence raise conflicts. Increased installation of gravity pipe projects around Mt. Kilimanjaro is an example. Establishment of Kirua-Kahe gravity water pipe has affected drainage of all irrigation canals that supplied water to Uparo. Comparable findings have been reported at Pangani (Komakech et al., 2011) and Rufiji River basins (Sokile et al., 2003).

We urge that successfully establishment of integrated water resource management (IWRM), like water user associations, could address effectively water challenges around Mt. Kilimanjaro. However, Tanzania still lacks a clear implementation framework for IWRM (URT, 2002).The concept of IWRM is not yet clear among local stakeholders (Sokile et al., 2003), thus expected benefits of this initiative have not been full realized on the ground. Despite several complexities related with implementation of IWRM (Biswas, 2008), we urge that this concept could have a potential to improve water management around Mt. Kilimanjaro if participatory approaches involving all local stakeholders will be adopted. Study by (Mehta and Movik, 2014) informed that social perspectives like political economy, gender, history and culture in shaping water management should not be overlooked when implementing IWRM practices in local communities.

The state mechanism for catchment protection is already established around Mt. Kilimanjaro (Kangalawe et al., 2014), however, cutting of trees can be easily spotted both in the national park and in home gardens. Apparently, local people also fail to recognize the importance of maintaining trees around water sources. The forest belt contributes the largest proportion of mountain discharge (Røhr and Killingtveit, 2003; Hemp, 2006), and the vegetation in the mountain forest plays an important role in mountain hydrology (Pócs, 1991; Schrumpf et al., 2011). Other ongoing disturbances around water sources include occasional wildfire and grazing (Lambrechts et al., 2002).

The supply of irrigation water around Mt. Kilimanjaro can be improved without increasing abstraction rates from sources. Regular repair and maintenance of canals, especially around upper areas, could improve conveyance efficiency and minimize water competition. Indeed, establishing lined canals could be too expensive for Chagga people. However, improvements can be prioritized where excessive leakages and physical damages are frequent. Agronomically, several techniques for soil and water conservation (SWC) have been used by Chagga for decades. This includes application of mulching, planting indigenous trees, establishing contour grass strips and terraces. Considering their importance, research is needed to investigate what prevents Chagga people from maintaining these conservation practices.

2.5 Conclusions and Recommendations

Gravity-based irrigation canals are still the major means of supplying agricultural water around Mt. Kilimanjaro. Among the three subregions of the study area, villages within the central part experience less supply of canal water. This was due to complex landscape geomorphology, which limits expansion of primary canals. Similarly, spatial variation of canal discharge was observed along the elevation gradient. Indeed, topographical factors and soil properties influenced the dynamics of canal discharge. However, management of agricultural water also has a significant impact on canal conveyance efficiency. Because an alternative supply of irrigation water is lacking, rising water demand intensify water competition on available sources. The supply of irrigation water around Mt. Kilimanjaro can be improved without increasing abstraction rates from sources. Regular repair and maintenance of canals, especially around upper areas could improve conveyance efficiency and minimize water competition. Indeed, establishing lined canals could be too expensive for Chagga people. However, improvements can be prioritized where excessive leakages and physical damages are frequent. Agronomically, several techniques for soil and water conservation (SWC) have been used by Chagga for decades. This includes application of mulching, planting indigenous trees, establishing contour grass strips and terraces. Additionally, traditional water harvesting techniques, like *Nduwas* could be promoted where small streams are not used because of their low discharge. Considering the socio-economic importance of water to mountain and downstream communities, efforts to improve canals water supply and the discharge capacity of their sources is inevitable. Furthermore, research is needed to investigate what prevent Chagga people from maintaining traditional techniques for conservation of agricultural water. The study findings from Mt. Kilimanjaro can be widely applied to other agro-ecosystems in Tanzania, since large proportion of irrigation schemes are still traditional and operate under high reliance on surface water sources.

Bibliography

Aberra, Y. (2004). Problems of the solution: intervention into small-scale irrigation for drought proofing in the mekele plateau of northern ethiopia, *The Geographical Journal* **170**(3): 226–237.

Ager, A., Stark, L., Sparling, T. and Ager, W. (2011). Rapid appraisal in humanitarian emergencies using participatory ranking methodology (prm), *New York, NY: Program on Forced Migration and Health, Columbia University Mailman School of Public Health* .

Amede, T. (2015). Technical and institutional attributes constraining the performance of small-scale irrigation in ethiopia, *Water resources and rural development* **6**: 78–91.

Bender, M. V. (2008). 'for more and better water, choose pipes!'building water and the nation on kilimanjaro, 1961–1985, *Journal of Southern African Studies* **34**(4): 841–859.

Beven, K. J. and Kirkby, M. J. (1979). A physically based, variable contributing area model of basin hydrology / un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant, *Hydrological Sciences Bulletin* **24**(1): 43–69.
URL: *https://doi.org/10.1080/02626667909491834*

Beven, K. J., Wood, E. F. and Sivapalan, M. (1988). On hydrological heterogeneity – catchment morphology and catchment response, *Journal of hydrology* **100**(1-3): 353–375.

Biswas, A. K. (2008). Integrated water resources management: is it working?, *International Journal of Water Resources Development* **24**(1): 5–22.

Boaten, B. A. (1998). Traditional conservation practices: Ghana's example, *Institute of African Studies Research Review* **14**(1): 42–51.

Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V. et al. (2017). An assessment of the global impact of 21st century land use change on soil erosion, *Nature communications* **8**(1): 2013.

Bos, M. G. and Nugteren, J. (1990). *On irrigation efficiencies*, number 19, ILRI.

Brossard, D., Lewenstein, B. and Bonney, R. (2005). Scientific knowledge and attitude change: The impact of a citizen science project, *International Journal of Science Education* **27**(9): 1099–1121.

Brouwer, C., Prins, K. and Heibloem, M. (1989). Irrigation water management: irrigation scheduling, *Training manual* **4**.

Carter, M. R. (1993). *Soil sampling and methods of analysis*, CRC Press.

Cleaver, F. and Toner, A. (2006). The evolution of community water governance in uchira, tanzania: The implications for equality of access, sustainability and effectiveness, *Natural Resources Forum*, Vol. 30, Wiley Online Library, pp. 207–218.

Clemmens, A. J. and Replogle, J. A. (1980). *Constructing simple measuring flumes for irrigation canals*, number 2268, Dept. of Agriculture, Science and Education Administration: for sale by the Supt. of Docs., US Govt. Print. Off.

Devenne, F. (2006). On 'the mountain of waters', the furrows are running dry: Rethinking mount kilimanjaro's irrigation system, *Kilimanjaro. Mountain, Memory, Modernity* pp. 201–214.

Dundas, C. (1924). Kilimanjaro and its people : A history of the wachagga, their laws, customs and legends, together with some account of the highest mountain in africa, *Technical report*, H.F & G Witherby.

Dungumaro, E. W. and Madulu, N. F. (2003). Public participation in integrated water resources management: the case of tanzania, *Physics and Chemistry of the Earth, Parts A/B/C* **28**(20-27): 1009–1014.

Durner, W., Iden, S. C. and von Unold, G. (2017). The integral suspension pressure method (isp) for precise particle-size analysis by gravitational sedimentation, *Water Resources Research* **53**(1): 33–48.

Fernandes, E. C., Oktingati, A. and Maghembe, J. (1985). The chagga homegardens: a multistoried agroforestry cropping system on mt. kilimanjaro (northern tanzania), *Agroforestry systems* **2**(2): 73–86.

Grove, A. (1993). Water use by the chagga on kilimanjaro, *African Affairs* **92**(368): 431–448.

Haile, M. (2005). Weather patterns, food security and humanitarian response in sub-saharan africa, *Philosophical Transactions of the Royal Society B: Biological Sciences* **360**(1463): 2169–2182.

Hastie, T. and Tibshirani, R. (1990). *Generalized Additive Models*, Chapman and Hall, New York.

Hemp, A. (2005). Climate change-driven forest fires marginalize the impact of ice cap wasting on kilimanjaro, *Global Change Biology* **11**(7): 1013–1023.

Hemp, A. (2006). The banana forests of kilimanjaro: biodiversity and conservation of the chagga homegardens, *Biodiversity & Conservation* **15**(4): 1193–1217.

Hennink, M. M. (2013). *Focus group discussions*, Oxford University Press.

Homewood, K. M. (2006). Politics in land and water management: study in kilimanjaro, tanzania.

Horton, R. E. (1945). Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology, *Geological society of America bulletin* **56**(3): 275–370.

Ikegami, K. (1994). The traditional agrosilvipastoral complex system in the kilimanjaro region, and its implications for the japanese-assisted lower irrigation projact, *African Study Monographs* **15**: 189–210.

IUSS Working Group WRB (2015). *World Reference Base for Soil Resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps*, World Soil Resources Reports No. 106. FAO, Rome.

Jadczyszyn, J. and Niedźwiecki, J. (2005). Relation of saturated hydraulic conductivity to soil losses., *Polish Journal of Environmental Studies* **14**(4).

Jasiewicz, J. and Metz, M. (2011). A new grass gis toolkit for hortonian analysis of drainage networks, *Computers & Geosciences* **37**(8): 1162–1173.

Kangalawe, R., Noe, C., Tungaraza, F., Naiman, G. and Mlele, M. (2014). Understanding of traditional knowledge and indigenous institutions on sustainable land management in kilimanjaro region, tanzania, *Open Journal of soil Science* **4**: 469–493.

Kitzinger, J. (1994). The methodology of focus groups: the importance of interaction between research participants, *Sociology of health & illness* **16**(1): 103–121.

Köhne, J. M., Alves Júnior, J., Köhne, S., Tiemeyer, B., Lennartz, B. and Kruse, J. (2011). Double-ring and tension infiltrometer measurements of hydraulic conductivity and mobile soil regions, *Pesquisa Agropecuária Tropical* **41**(3): 336–347.

Komakech, H., van Koppen, B., Mahoo, H. and van der Zaag, P. (2011). Pangani river basin over time and space: On the interface of local and basin level responses, *Agricultural Water Management* **98**(11): 1740–1751.

Krueger, R. A. and Casey, M. A. (2014). *Focus groups: A practical guide for applied research*, Sage publications.

Kuyah, S., Öborn, I. and Jonsson, M. (2017). Regulating ecosystem services delivered in agroforestry systems, *Agroforestry*, Springer, pp. 797–815.

Körner, C. (2004). Mountain biodiversity, its causes and function, *Ambio* **Spec No 13**: 11—17.
URL: *http://europepmc.org/abstract/MED/15575177*

Lambrechts, C., Woodley, B., Hemp, A., Hemp, C., Nnyiti, P. et al. (2002). Aerial survey of the threats to mt. kilimanjaro forests, *Technical report*, United Nations Development Programme (UNDP).

Maganga, F. (1998). Indigenous knowledge and irrigation development in tanzania: Experiences from msanzi, nyeregete and musa mwijanga farmer-managed irrigation schemes, *Scandinavian Seminar College on African Perspectives on Policies and Practices Supporting Sustainable Development, Harare.*

Maganga, F. P. (2003). Incorporating customary laws in implementation of iwrm: some insights from rufiji river basin, tanzania, *Physics and Chemistry of the Earth, Parts A/B/C* **28**(20-27): 995–1000.

Maghimbi, S. (2007). Recent changes in crop patterns in the kilimanjaro region of tanzania: the decline of coffee and the rise of maize and rice, *African study monographs* **35**: 73–83.

Makurira, H., Mul, M., Vyagusa, N., Uhlenbrook, S. and Savenije, H. (2007). Evaluation of community-driven smallholder irrigation in dryland south pare mountains, tanzania: A case study of manoo micro dam, *Physics and Chemistry of the Earth, Parts A/B/C* **32**(15-18): 1090–1097.

Martz, L. W. and Garbrecht, J. (1993). Automated extraction of drainage network and watershed data from digital elevation models, *JAWRA Journal of the American Water Resources Association* **29**(6): 901–908.

Mehta, L. and Movik, S. (2014). Flows and practices: Integrated water resources management (iwrm) in african contexts, *IDS Working Papers* **2014**(438): 1–34.

Misana, S. (1991). The importance of mount kilimanjaro and the needs for its integrated management and conservation, *The Conservation of Mount Kilimanjaro. IUCN, Gland, Switzerland and Cambridge, UK* .

Misana, S. B., Sokoni, C. and Mbonile, M. J. (2012). Land-use/cover changes and their drivers on the slopes of mount kilimanjaro, tanzania, *Journal of geography and Regional Planning* **5**(8): 151.

Nakawuka, P., Langan, S., Schmitter, P. and Barron, J. (2017). A review of trends, constraints and opportunities of smallholder irrigation in east africa, *Global Food Security* .

Ngigi, S. N., Savenije, H. H., Thome, J. N., Rockström, J. and de Vries, F. P. (2005). Agro-hydrological evaluation of on-farm rainwater storage systems for supplemental irrigation in laikipia district, kenya, *Agricultural Water Management* **73**(1): 21–41.

O'Callaghan, J. F. and Mark, D. M. (1984). The extraction of drainage networks from digital elevation data, *Computer vision, graphics, and image processing* **28**(3): 323–344.

Pócs, T. (1991). The significance of lower plants in the conservation of mount kilimanjaro, *The Conservation of Mount Kilimanjaro. The IUCN Tropical Forest Programme* pp. 21–34.

R Core Team (2018). *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria.
URL: *https://www.R-project.org/*

Riley, S. J. (1999). Index that quantifies topographic heterogeneity, *intermountain Journal of sciences* **5**(1-4): 23–27.

Røhr, P. C. and Killingtveit, Å. (2003). Rainfall distribution on the slopes of mt kilimanjaro, *Hydrological sciences journal* **48**(1): 65–77.

Schrumpf, M., Axmacher, J. C., Zech, W. and Lyaruu, H. V. (2011). Net precipitation and soil water dynamics in clearings, old secondary and old-growth forests in the montane rain forest belt of mount kilimanjaro, tanzania, *Hydrological processes* **25**(3): 418–428.

Shen, J. (1981). *Discharge characteristics of triangular-notch thin-plate weirs*, number 1617, United States Department of the Interior, Geological Survey.

Soini, E. (2005). Land use change patterns and livelihood dynamics on the slopes of Mt. Kilimanjaro, Tanzania, *Agricultural Systems* **85**(3): 306–323.

Sokile, C. S., Kashaigili, J. J. and Kadigi, R. M. (2003). Towards an integrated water resource management in tanzania: the role of appropriate institutional framework in rufiji basin, *Physics and Chemistry of the Earth, Parts A/B/C* **28**(20): 1015–1023.

Strahler, A. N. (1957). Quantitative analysis of watershed geomorphology, *Eos, Transactions American Geophysical Union* **38**(6): 913–920.

Tagseth, M. (2008). and the development of indigenous irrigation. methods and examples from kilimanjaro, tanzania., *Norsk Geografisk Tidsskrift - Norwegian Journal of Geograph* **14**(3).

Turpie, J., Ngaga, Y. M. and Karanja, F. (2005). Catchment ecosystems and downstream water: the value of water resources in the pangani basin, tanzania, *Iucn water, nature and economics technical paper no. 7*, The World Conservation Union, Ecosystems and Livelihoods Group Asia.

Udawatta, R. P., Gantzer, C. J. and Jose, S. (2017). Agroforestry practices and soil ecosystem services, *Soil Health and Intensification of Agroecosytems*, Elsevier, pp. 305–333.

URT (2002). *The National Water Policy 2002, United Republic of Tanzania*, Ministry of Water and Livestock.

Vågen, T., Shepherd, K. D., Walsh, M. G., Winowiecki, L., Desta, L. T. and Tondoh, J. E. (2010). Afsis technical specifications: soil health surveillance, *Africa Soil Information Service (AfSIS). Nairobi, Kenya: World Agroforestry Centre* .

Wachyan, E. and Rushton, K. (1987). Water losses from irrigation canals, *Journal of Hydrology* **92**(3-4): 275–288.

Wang, L. and Liu, H. (2006). An efficient method for identifying and filling surface depressions in digital elevation models for hydrologic analysis and modelling, *International Journal of Geographical Information Science* **20**(2): 193–213.

Wiesmann, U., Gichuki, F. N., Kiteme, B. P. and Liniger, H. (2000). Mitigating conflicts over scarce water resources in the highland-lowland system of mount kenya, *Mountain Research and Development* **20**(1): 10–15.

Winter, C. J. (1994). Some problems of chagga identity, *Sprachen und Sprachzeugnisse in Afrika: Eine Sammlung Philologischer Beiträge Wilhelm JG Möhlig zum* **60**: 459–471.

Zech, M., Hörold, C., Leiber-Sauheitl, K., Kühnel, A., Hemp, A. and Zech, W. (2014). Buried black soils on the slopes of Mt. Kilimanjaro as a regional carbon storage hotspot, *CATENA* **112**: 125–130.

Chapter 3

Water management under traditional farming systems: Practices and limitations of the Mfongo system around Mt. Kilimanjaro

J. Kimaro [1*], and C. Bogner [2].
[1]Tanzania Wildlife Research Institute, Tanzania
[2]Ecosystem Research, Institute of Geography, University of Cologne, Zülpicher Straße 45, 0674 Cologne, Germany

Corresponding author: J. Kimaro. Email: jerome.kimaro@tawiri.or.tz

Published in Water Utility Journal. 22: 53-64, 2019.

Abstract

The southern slopes of Mt. Kilimanjaro host one of the oldest traditional irrigation systems in Tanzania, locally known as *Mfongo*. Today, the system is facing several challenges that affect local livelihoods and the provision of other ecosystem services. To study the structure of the traditional irrigation systems and their management limitations in the southern slopes of Mt. Kilimanjaro, Tanzania, an interview survey was conducted whereby focus group discussions and key informants were used as the main tools for data collection. Study findings suggest that current water uses under the *Mfongo* system are not sustainably managed, thus leading to an imbalanced water supply among key users. The system is characterized by low water conveyance efficiency and high losses during storage. Disturbances in catchment areas have increased and community participation in canals management has declined. Moreover, poor technical support, conflicting policies and unequal opportunities to land ownership limit local efforts dedicated to improving irrigation activities around Mt. Kilimanjaro. There is an urgent need for technical research on alternative options for agricultural water supply in the area and a need of minimizing water losses from supplying and storage infrastructures.

Keywords: *Irrigation water*, *Mfongo system*, *agriculture*, *Chaggas*, *local people*, *Mt. Kilimanjaro*.

3.1 Introduction

Traditional irrigation systems still constitute the largest share of agricultural water supply in most developing countries, most of them confined within mountainous areas (Beall, 2002; Jodha, 2001). They support agricultural production and biogeochemical processes important for community livelihood and ecosystem functioning (Spehn et al., 2006). Nevertheless, traditional irrigation systems have increasingly become vulnerable for diverse reasons, thus affecting the sustainable supply of water to communities. Although global climate changes reported impacting the hydrological dynamics in mountainous regions (Bruijnzeel et al., 1990), the severity of these effects is probably not sufficient to explain the decrease in the water supply that we witness today.

Increased water withdrawal is already a serious concern following the rapid expansion of cultivation areas, changes in crop types, and agronomic practices (Misana et al., 2012; Tagseth, 2008). Additionally, to increased overall food demands, the modern human communities have shifted their food preferences which affect the overall supply chain, production decisions, and ultimately quality of landscapes. Current production systems are characterized by increased water use with less control of sediment run-off, nutrients loss, and pollution from agrochemicals (Kimaro et al., 2008). Additionally, poor governance of water resources and unequal rights to land ownership jeopardize efforts dedicated to improving its management (Marson and Savin, 2015; Valipour, 2015).

Poor understanding of the organization of traditional irrigation systems impacts the sustainable management of water resources. In this study, we hypothesize that the current management of the mountain canal system influences an imbalance in the water supply. Drawing an example from the traditional irrigation system, *Mfongo*, around Mt. Kilimanjaro, we assess the local narratives regarding the effectiveness of irrigation structure and its management limitations. textitMfongo system has been used for centuries, to sustain home gardens and other farming systems on the southern slopes of Mt. Kilimanjaro (Fernandes et al., 1985). However, water supply from canals has been decreasing over time, thus threatening future food production and the provision of other ecosystem services.

This study offers an opportunity to evaluate and design appropriate strategies for better agricultural water management in the way that crops' requirements for water are met, farmers reach their production targets and, at the same time, natural resources are protected in mountain ecosystems.

3.2 Materials and Methods

3.2.1 Study area

The study area (Figure 3.1) is located at the southern slope of Mt. Kilimanjaro, between 2°45′ and 3°25′S and 37°00′ and 37°43′E. This study was conducted starting from the plains (900 m) up to the forest boundary (1600 m). Major land use in this area is influenced by the elevational gradient, whereby the lower area is dominated by maize monocropping and extensive pastoralism. In the mid-area (1200 – 1350 m), the dominant farming systems are coffee-banana agroforestry and increasingly also maize fields. There are several coffee estates operated as large-scale farming. In the upper areas (1350 – 1600 m), the tree-based agroforestry, in particular, Chagga home gardens have been practiced for decades by local inhabitants with banana and coffee as dominant crops (Hemp, 2006; Soini, 2005).

Two distinct rainy seasons occur in the study area: the long rains starting from mid-March and continuing until the end of May, while the short rains occur between October to December. Occasionally, short rains extend to the end of January of the following year. The driest period is from July to the end of September, while April and May are the wettest months. Mean annual rainfall varies between 600 – 900 mm in lower areas, 1000 – 1200 mm in mid-areas, and 1800 – 2000 mm in upper areas crops (Misana et al., 2012). The soil type varies along the slope, whereby fine-textured clay soil is predominant in the lower area, compared to the coarser textured volcanic soil in upper areas (Mpanda et al., 2016; Zech et al., 2014).

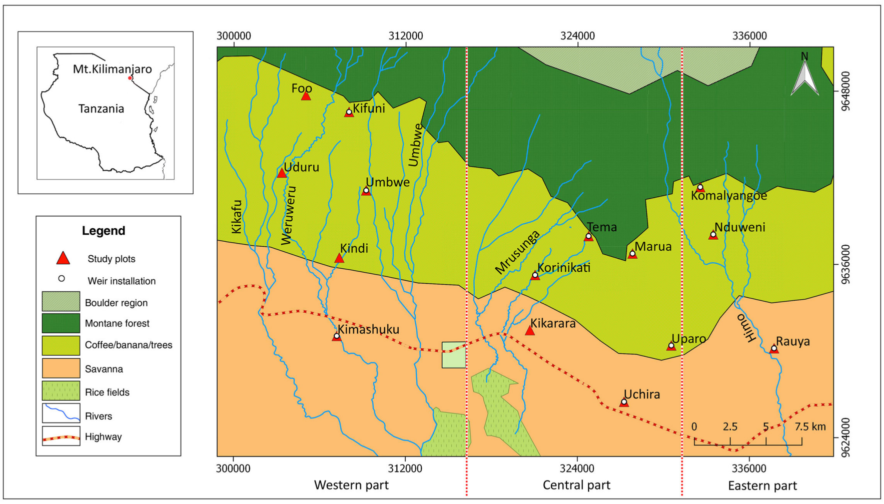

Figure 3.1: The study area (Google Maps, 2017) indicating distribution of study villages (map adopted from Kimaro et al., 2019)

3.2.2 Methods

3.2.3 Socio-economic surveys

We collected socio-economic information during Focus Groups Discussions (FGDs) and key informants interviews (KIs). The former involved discussions with groups of villagers (10-15 people) from 15 selected villages. Open-ended questions were used to guide discussions, which aimed at obtaining local perceptions on the traditional irrigation system and its major constraints. Diverse social groups of villagers like women, elderly people, affluent ones, and leaders were involved (Dollisso and Martin, 1999). Confidentiality of villagers' identities and their contribution was considered important and ethical (Krueger and Casey, 2014). Contributions from KIs were obtained through interviews with the government officials like district officers from Hai and Moshi Rural Councils, the Pangani Basin Water Office (PBWO) Moshi and the Northern Zone Irrigation Office. Similarly, a set of open-ended questions was used to guide these discussions.

3.2.4 Mapping irrigation schemes

Uduru irrigation scheme located in the Uduru village was selected as representative. The mapping exercise involved a participatory resources mapping technique (Tripathi and Bhattarya, 2004), whereby villagers were guided to develop a hand sketch map of their irrigation scheme. Villagers were divided into three groups comprised of 3-5 participants. Each group was given a piece of paper and maker-pen to present their knowledge about the scheme structure. The following details were presented on the map: (i) canals intake sources, (ii) routes of primary, secondary, and tertiary canals, (iii) orientation of crop fields. Finally, we combined presented ideas into one final version that was agreed upon by all participants. The map was then scanned and imported into the computer. From the scanned images, new vector layers were created to mirror the details of the hand-sketched map. All graphics work was completed by using Adobe Illustrator software, version CS 6 (Team, 2012).

3.2.5 Data analysis

Descriptive statistics were used to provide a statistical summary of all information related to the management of canals. Additionally, qualitative information was analysed by using content analysis in order to categorize verbal data for purpose of classification and summarization (Hennink, 2013). All supporting statements were quoted in the text as personal communication (pers. com.). To assess agreement among participants' opinions during a participatory mapping exercise, Kendall's coefficient of concordance (W) was used (Field, 2014). W values ranges from 0 (no agreement) to 1 (complete agreement). We employed R software for analysis (R Core Team, 2018).

3.3 Results

3.3.1 Structure and functions of the Mfongo system

The mountain *Mfongo* network comprises several clusters of traditional irrigation schemes which are scattered across the southern slopes of Mt. Kilimanjaro, with more concentration around the western and eastern parts. According to key informants, the size of irrigation schemes varies in terms of land size, the number of users, and a number of canals. Given the enormous size of the area, we were not able to quantify these details. It was further mentioned that more than 90% of all canals were unlined and some run more than 5 km from their sources. Given that canal flow is gravity-driven, its construction involves many turns to avoid raised terrain. Notably, the use of aqueducts is not common around Mt. Kilimanjaro. Occasionally, pieces of chopped wood, scraped metal, or banana stems are used to bridge water across smaller depressions.

A network of canals is the major component of irrigation schemes. Canals were categorized based on their relative size and the order of arrangement from the source, namely, primary, secondary and tertiary furrows (Fig. 2A). Primary canals, like Mwaana and Mrema in Uduru irrigation schemes, collected water from a river, thus considered as the major water entry point into the scheme. Down the stream, primary canals branched into several secondary canals. They were smaller compared to primary canals. Finally, each secondary canal was further subdivided into the smallest canals called tertiary canals. We noted that tertiary canals were the main structures that supplied water to the crop fields.

Apart from the canal network, the irrigation schemes comprised several small earth dams, locally known as Nduwas (Fig. 3). They were intentionally established to sustain canal water supply during dry seasons or where sources have lower discharge. Normally, overnight discharge is collected and used for irrigation on the following day. The most important feature in *Nduwas* is the crest, a vertical earth wall strengthened by roots of some selected tree species, common ones were *Albizia julibrissin*, *Ficus sycomorus* and *Ailanthus altissima*. Likewise, a tunnel or *Kipogoro* with a stopper *Isasi* is established near the bottom of the crest, whose drainage is controlled by a piece of flat wood adjusted by a rope attached to a tree. This local engineering work is constrained by excessive seepage, and their maintenance is labor-intensive. The actual number of *Nduwa* could not be established. However, over 80% of FGD participants from all villages mentioned that only a few Nduwa are operating today around the study area.

More than 80% of FGDs participants reported using canals for irrigating crops at different times of the year. Interestingly, farmers took advantage of soil wetness along canals by growing several crops varieties, common ones included sugar cane, taro, banana, and several varieties of vegetables. Since canal water is free of charge, a significant proportion of villagers (65%) considered using them as a potential strategy of minimizing tap water bills. On the other hand, the daily per capita consumption of 25 litres is far below actual water needs in rural households around Mt. Kilimanjaro. For example, the water need of stall-fed cattle was reported to be two to three times that amount. Over 70% of meeting, participants reported keeping dairy cattle.

3.3.2 Conveyance and field application efficiency of canals

A number of indicators revealed that the mechanism of water abstraction, transport, storage and field application in the study area is largely inefficient. At the intake points, a part of the river flow was obstructed by a pile of stones, sandbags or vegetation trashes to direct water towards the primary canal's head. Notably, these structures are not durable and demand frequent maintenance. Moreover, most of the canal intakes are located inside the forest, far away from villages. Yet, villagers should seek a permit from the Kilimanjaro National Park (KINAPA) before entering the forest. This bureaucratic approach often delays necessary maintenance. Along the canals, excessive water loss through seepage was noted. We could not quantify the actual amount of water that was lost. However, visual observation revealed a wide wetted perimeter, approximately 1 m, on each side of the canals. By construction, the earth piled on each side of the canal has a weak mechanical strength, insufficient to prevent physical damage. Participants of FGDs reported a number of potential risks that could lead to decreasing water conveyance efficiency in canals. This included animal trampling (75%), especially free-grazing livestock (Fig. 5). Similarly, villagers pay insufficient attention to weak canal banks when collecting water for domestic uses or cutting livestock fodder along canals (80%). Additionally, some biological activities in the soil were related to excessive water loss from canals (68%). Common ones were perforations and holes created by stream crabs, termites, and mole rodents.

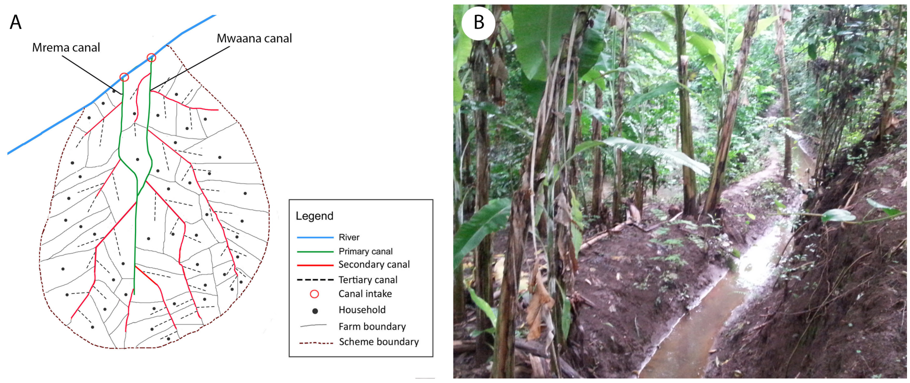

Figure 3.2: (A) A hand sketch of a traditional irrigation scheme in Uduru Village showing canal sources and a network of primary, secondary and tertiary canals, (B) A primary canal delivering water to the scheme.

3.3.3 Irrigation practices under different farming systems

It was noted that traditional ways of crop irrigation around Mt. Kilimanjaro were inefficient in terms of water consumption and time management. Between 3 and 4 hours may be spent to irrigate just one hectare. Extra time may be needed in case of any interruption that may block canal water flow, thus demanding a farmer to walk upstream tracing the cause.

Figure 3.3: A small water dam or *Nduwa* used for temporary water storage or sustaining flow of weakly discharging canals

Figure 3.4: Ecosystem services derived from unlined traditional irrigation canals. (A) Diverse food crops planted along canals, and (B) a young boy collecting water for domestic uses.

Figure 3.5: Livestock trampling over canal banks can accelerate water leakage from canals.

On the other hand, irrigation practices varied with the type of farming system (Figure 3.7). In vegetable or maize fields, the water supply between crops is more or less systematic. Checks in the form of rectangular ridges were established to hold water once received from the tertiary canal. Once full, the check at the lower side is opened by hand how to allow the flow to the next trough, and so forth. In home garden agroforestry, crops were not planted in confined troughs, as observed in maize or vegetable plots, thus water supply to crops was controlled by farmers. Irrigation practices in both farming systems involved extended foot trafficking on the wet soil and thus probably soil compaction and a long duration of work. Additionally, the amount and duration of water supply to crops rely on farmers' experience or availability of water.

Figure 3.6: (A) Irrigation water management under vegetable farming and (B) home gardens around Mt. Kilimanjaro.

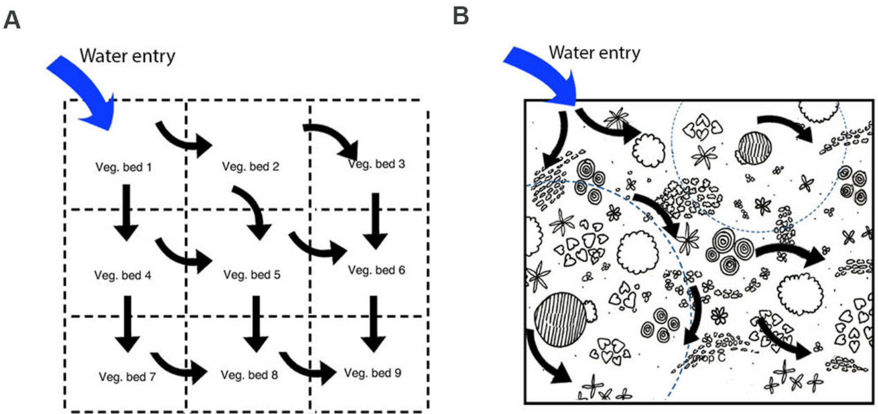

Figure 3.7: (A)Traditional water supply patterns in vegetable farming and (B) in home gardens.

3.3.4 Weakness of resource governance

Weak cohesion between water management authorities and local communities is the most pronounced water management concern around Mt. Kilimanjaro. It was commented during the FDGs that formal authorities operate through a top-down approach, which weakens social ties with communities. Villagers are provided little room for collaboration, including presenting their opinions or participating in decision-making. Increased installation of gravity-based pipes by district authorities was reported to affect the discharge of traditional canals. Most villages in the central part of the mountain slope, like Uchira and Uparo have had no access to canal water since the early 2000s. In spite of this weakness, efforts to establish new arrangements for water management between local and government authorities have not been considered.

On the other hand, KIs reported that the internal changes within Chagga communities have weakened the authoritative capacity of local institutions. The authority of clan heads over community furrow work has been highly disintegrated. Currently, most local institutions play only a minor role, confined within the vicinity of their village. A lack of sufficient labour required for canal maintenance and the unwillingness of young people to participate in canal maintenance, leave the burden to a few people. Additionally, collective responsibilities among local people, like attending funerals or harvesting also limit effective participation in furrow work. Most furrows are repaired between June to August, which is also the peak harvesting season of beans and maize. Between 15 and 20 people are required to complete furrow repair within a one-week period. But much effort is needed to mobilize people and yet takes longer to accomplish the same task.

Figure 3.8: The remnant of an abandoned irrigation canal following poor community participation in canal maintenance.

Furthermore, contradicting national sectoral policies seem to mislead local decisions related to water management. For example, the *Kilimo Kwanza* (Swahili for agriculture first) was implemented to improve food security. However, there is an increased focus on commercial agricultural production, with far-reaching implications on the governance of water resources. Criticism about the misinterpretation of the *Kilimo Kwanza* policy has been reported by forest officers around Mt. Kilimanjaro. Politicians are falsely taking advantage of the policy statements to re-establish their local popularity. Concurrently, an increased number of farmers have used the policy as an excuse to encroach restricted areas. Disturbances around protected areas like lower mountain forests, riparian vegetation along rivers, and around springs were easily spotted. However, it was weakly agreed (30%) by villagers that they are also involved in forest encroachment.

3.3.5 Lack of technical and financial support

The majority of FGDs participants (85%) have not been in contact with agricultural extension Kibosho, have been in contact with coffee extension officers from Tanzania Coffee Research Institute (TACRI) to learn general management practices of agroforestry. Only a few examples of specialized technical education regarding the management of furrows and water supply have been developed by responsible authorities (Pers. com.). This includes the establishment of rice farming at Lower Moshi and Mabogini areas through the support of the development cooperation agency of Japan (JICA). It was mentioned that introduction of this scheme had a significant impact on livelihood transformation in terms of increased income and food security. Likewise, through the support of United Nations Development Programme (UNDP), a traditional scheme was improved at Uduru village in the early 2000s (Pers. com.).

Furthermore, we noted that private sectors and NGOs could be useful to promote improved irrigation activities around Mt. Kilimanjaro like in other parts of the country. During our field visit, we learned that several micro-financing services operate in villages around Mt. Kilimanjaro.

3.3.6 Influence of gender and land rights on management of canals

Traditional taboos that restrict women to participate in canal maintenance still exist around Mt. Kilimanjaro. However, 65% of respondents informed that the restrictions are gradually changing, as the number of women heading a household increases. Similarly, spatial variation of gender segregation was observed along the elevational gradient. In villages located in the lower elevation zone, more women participated in cleaning and repairing canals, compared to their counterparts in the higher altitudes. Additionally, we noted a strong connection between gender, land rights, and water management within Chagga communities. Since land (*Kiamba*) is normally inherited by sons only, women have less control and authority on land resources including irrigation canals.

On the other hand, a significant proportion of villagers around Mt. Kilimanjaro were reported to lack permanent land ownership. They operate plots on the basis of renting or taking care of a relative who stays away. The majority of interviewed villagers (65%) mentioned that land tenant is likely to avoid commitment to install improved irrigation infrastructures or participate effectively in maintaining canals, given that farm investments take a long time to pay back

3.4 Discussion and conclusion

3.4.1 Structural functions of Chaggas irrigation schemes

Seemingly, water supply from traditional canals is highly variable across the study area. While communities in the eastern and western parts have been well-endowed with canals, most villagers in the central parts could be highly vulnerable to water scarcity. We attribute this to the complex landscape that limits most villages to access canals (Kimaro et al., 2019). Additionally, water flow in canals is gravity-based (Tagseth, 2008). However, the overall agricultural production potential could be different from one scheme to another due to the variable size of schemes, the number of canals, and a number of water users. Thus, schemes characterized by many users and a low number of canals could be experiencing water shortage and frequent social conflicts related to competition over water. Relationships between water availability, crop yield, and water conflicts have also been reported in other smallholder irrigation schemes (Tognetti et al., 2006; Veldwisch et al., 2013).

The observed order of canals revealed that old Chaggas had good skills and application knowledge of fluid mechanics since the size of canals decreased from the intake source downwards. Despite the fact that water flow in mountainous areas is largely influenced by slope (Beven and Kirkby, 1979), water velocity increases when it flows towards small canals as described in Bernoulli's law of fluid dynamics (Munson et al., 2013). Notably, some parts of the landscape are relatively flat, like Lyamungo Kati and Uduru villages, yet we observed some canals flowing more than 5 km from their sources.

The future sustainability of micro-dams (Nduwa) around Mt. Kilimanjaro is still questionable for a number of reasons. Traditional technical knowledge is poorly transmitted to young generations (Kangalawe et al., 2014). Only few trees species are recommended for the construction of Nduwa (Pers.com.). However, as indigenous trees are increasingly replaced by exotic ones (Misana et al., 2003), tree species important for the construction of *Nduwa* could also be lacking. Additionally, Nduwas are highly vulnerable to siltation, and labour required for their maintenance is not readily available. Therefore, the irrigation system should be combined with other economic activities as an incentive to villagers' participation in the management of irrigation structures. In Sri Lanka, for example, fishing has been introduced successfully as a promotion of multiple-use of irrigation water (Renwick, 2001).

3.4.2 Water conservation under traditional irrigation practices

Generally, traditional ways of supplying irrigation water and their field application around Mt. Kilimanjaro are largely inefficient. Excessive water loss during water conveyance or storage, suggests a need of minimizing water seepage. Given that majority of local farmers around the study area have low income (NBS, 2013), introducing concrete-lined canals could be infeasible. Therefore, farmers should be assisted to identify areas where the soil is highly permeable. This is attributed to physical properties of the soil, like texture or natural cracks (Haghnazari et al., 2015). Additionally, a high population of rodents, termites, and stream crabs can easily damage unlined canals. To overcome this threat, cheap options, like the application of plastic sheets, have been successfully attempted in small-holder farming (Schibi, 2004). (Schibi, 2004).

Attempts to minimize potential risks to canal structure could enhance water conservation. Expanding tap water networks near homesteads and enforcing restrictions on grazing livestock could reduce trampling on canals walls. Uncontrolled livestock could be the source of water pollution (Hooda et al., 2000). Additionally, uncontrolled livestock affect crop yield and trigger social conflicts between livestock owners and farmers (Hussein et al., 1999).

Harvesting rainwater could reduce pressure to use canal water. Upper elevation zones of Mt. Kilimanjaro receive high and frequent precipitation (Hemp, 2006), thus can spare a large share of canal water to downstream users. Additionally, conservation agriculture practices, like mulching and application of organic amendments, could reduce excessive use of water for irrigation (Cook et al., 2006). Despite the prevailing water shortage around Mt. Kilimanjaro, the adoption of water harvesting technologies is far below expectation (pers. com.). A study is recommended to investigate potential barriers that influence the limitations.

It is worth noting, however, that the connection between causes and impacts on water management in the *Mfongo* system is variable at spatial scales. For example, the impacts of increased abstraction in gravity-based pipes on canal discharge in River Uchira were realized some years later and not immediately. Likewise, deforestation in upper catchment areas could lead to increased flood risks at lower slopes. Although flood events on the lower areas of Mt. Kilimanjaro were not frequently reported, the geomorphology of the landscape indicates that most villages in this area could be vulnerable to flooding.

Furthermore, we realized that the water demand varied along the mountain slope and across different farming systems. We attribute this to structural functions of irrigation systems, management of canals, and related social aspects of resources governance around Mt. Kilimanjaro. For example, canals around upper areas experience higher water losses during water conveyance, while increased vegetable production in lower areas intensifies the water demand. Our findings concur with observations by (Turpie et al., 2005), who observed the effect of changing crop preferences and market demands on irrigation water supply around Mt. Kilimanjaro.

3.4.3 Socio-economic implications of traditional irrigation practices

Irrigation canals around Mt. Kilimanjaro are un-gauged. Therefore, it is difficult to estimate the cost of agricultural production under small-holder farming. Additionally, the use of hand-hoe to manipulate water supply around crop root zone has a number of disadvantages to farmers. Too much time that could be economically useful to other chores is spent irrigating a small area. In home gardens, high variability of crop types suggests that some crops receive more or less water, compared to their actual demand. Additionally, irrigation involves too much foot trafficking on wet soil. Through this, the soil could be compacted if irrigation is conducted successively for many years

Despite the weakness of using hand hoe, we did not find other alternatives that Chagga people could use to control canal water during irrigation. In other small-holders agricultural landscapes in Tanzania, the use of small irrigation pumps has been promoted (Villholth et al., 2013). However, this option could be challenging around Mt. Kilimanjaro, since direct pumping from streams and rivers is not allowed (Turpie et al., 2005). Concurrently, water volume in tertiary canals is not sufficient to run a pump, unless collection ponds are established.

The use of irrigation pumps could be a solution to water losses in canals. However, its implementation could reduce the number of co-benefits that the traditional canal system provides to the community. The canal network is a cultural heritage to Chagga people. They carried names of people who initiate them, symbolize power, and are linked to a number of past events (Dundas, 1924; Tagseth, 2008). Additionally, permanently wet soil along canals is a hot spot for medicinal herbs and wild vegetables (Pers. com.).

3.4.4 Influence of policies, land rights and gender to the management of Mfongo system

Institutional problems related to water management like those around Mt. Kilimanjaro have been reported in many other catchment areas in Tanzania (Sokile et al., 2003; Vedeld et al., 2016). However, the fragility of mountain ecosystems has not been given sufficient attention. Instead, blanket recommendations have been widely applied across different agro-ecological zones (Kimaro et al., 2019). From a social perspective, livelihood in mountain communities is highly diverse. It is strongly connected to mother nature and traditional practices (Braun, 2003). Therefore, policy guidelines related to water management should emphasize participatory and holistic approaches that take into consideration various socio-economic differences, like economic capacity, education, and local perceptions. Solid knowledge of the local environment should be well integrated into planning and decision-making.

The persisting land ownership problem is an indication that a significant proportion of local people could be avoiding full participation in canal management. We link permanent land access to personal decisions on land-based investments. Establishing improved irrigation canals or frequent involvement in their management demands an individual's time and financial resources. Small-holder farmers face unforeseen risks, like unreliable agricultural market (Salami et al., 2010), and therefore could be avoiding investing their resources where tenure period is not guaranteed. However, we could not quantify the proportion of farmers who rely on rented land around Mt. Kilimanjaro. Therefore, it is worthwhile to conduct a further assessment on how customary land rights influence the management of water resources around Mt. Kilimanjaro. Similar to land rights issues, unbalanced access to canal water between men and women could be detrimental to the overall food production system. Cultural barriers that limit full participation of *Chagga* women in canal management and accessing water should be considered as something of the past. Since women play a more important role in agriculture than men (Boserup et al., 2013), there is a need to empower their participation in agricultural water management. We suspect that Chagga women could better understand farm conditions, including characteristics of the soil and performance of different crops, compared to their husbands.

This study has delivered a strong indication that increased water demand and ecosystem disturbances around Mt. Kilimanjaro are vulnerable to several future threats. We attribute this to impact further on the overall functioning of the ecosystem and community livelihood. Current patterns of water demands would put additional pressure on already destabilized hydrological systems and limit any effort dedicated to improving or restoring their functioning. Moreover, the results presented in this study are not sufficient to address the socio-economic consequences of poor management of irrigation canals in Mt. Kilimanjaro. Therefore, we recommend further studies to validate our findings and generate more findings related to sustainable water use in mountain agroecosystems.

Bibliography

Beall, C. (2002). Human dimensions of global mountain biodiversity. in: Mountain biodiversity. a global assessment, *Technical report*, Parthenon Publishing Group.

Beven, K. J. and Kirkby, M. J. (1979). A physically based, variable contributing area model of basin hydrology/un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant, *Hydrological Sciences Journal* **24**(1): 43–69.

Boserup, E., Tan, S. F. and Toulmin, C. (2013). *Woman's role in economic development*, Routledge.

Braun, A. (2003). *Managing natural resources for sustainable livelihoods: uniting science and participation*, IDRC.

Bruijnzeel, L. A. et al. (1990). Hydrology of moist tropical forests and effects of conversion: a state of knowledge review., *Hydrology of moist tropical forests and effects of conversion: a state of knowledge review.* .

Cook, H. F., Valdes, G. S. and Lee, H. C. (2006). Mulch effects on rainfall interception, soil physical characteristics and temperature under zea mays l, *Soil and tillage research* **91**(1-2): 227–235.

Dollisso, A. D. and Martin, R. A. (1999). Perceptions regarding adult learners' motivation to participate in educational programs., *Journal of agricultural education* **40**(4): 38–46.

Dundas, C. (1924). Kilimanjaro and its people : A history of the wachagga, their laws, customs and legends, together with some account of the highest mountain in africa, *Technical report*, H.F & G Witherby.

Fernandes, E. C., Oktingati, A. and Maghembe, J. (1985). The chagga homegardens: a multistoried agroforestry cropping system on mt. kilimanjaro (northern tanzania), *Agroforestry systems* **2**(2): 73–86.

Haghnazari, F., Shahgholi, H. and Feizi, M. (2015). Factors affecting the infiltration of agricultural soils, *International Journal of Agronomy and Agricultural Research* **6**(5): 21–35.

Hemp, A. (2006). Ecology and altitudinal zonation of pteridophytes on mt. kilimanjaro, *African Plants: Biodiversity, Ecology, Phytogeography and Taxonomy* .

Hennink, M. M. (2013). *Focus group discussions*, Oxford University Press.

Hooda, P., Edwards, A., Anderson, H. and Miller, A. (2000). A review of water quality concerns in livestock farming areas, *Science of the total environment* **250**(1-3): 143–167.

Hussein, K., Sumberg, J. and Seddon, D. (1999). Increasing violent conflict between herders and farmers in africa: claims and evidence, *Development policy review* **17**(4): 397–418.

Jodha, N. (2001). Sustainable agriculture in fragile resource zones: technological imperatives, *in* N. Jodha (ed.), *Life on the Edge: Sustaining Agriculture and Community Resources in Fragile Environments*, Oxford University Press, New Delhi.

Kangalawe, R., Noe, C., Tungaraza, F., Naiman, G. and Mlele, M. (2014). Understanding of traditional knowledge and indigenous institutions on sustainable land management in kilimanjaro region, tanzania, *Open Journal of soil Science* **4**: 469–493.

Kimaro, D., Poesen, J., Msanya, B. and Deckers, J. A. (2008). Magnitude of soil erosion on the northern slope of the uluguru mountains, tanzania: Interrill and rill erosion, *Catena* **75**(1): 38–44.

Kimaro, J. G., Scharsich, V., Huwe, B. and Bogner, C. (2019). Distribution of traditional irrigation canals and their discharge dynamics at the southern slopes of mount kilimanjaro, *Frontiers in Environmental Science* **7**: 24.

Krueger, R. A. and Casey, M. A. (2014). *Focus groups: A practical guide for applied research*, Sage publications.

Marson, M. and Savin, I. (2015). Ensuring sustainable access to drinking water in sub saharan africa: conflict between financial and social objectives, *World Development* **76**: 26–39.

Misana, S. B., Majule, A. E. and Lyaruu, H. V. (2003). Linkages between changes in land use, biodiversity and land degradation on the slopes of mount kilimanjaro, tanzania.

Misana, S. B., Sokoni, C. and Mbonile, M. J. (2012). Land-use/cover changes and their drivers on the slopes of mount kilimanjaro, tanzania, *Journal of geography and Regional Planning* **5**(8): 151.

Mpanda, M., Sinclair, F. and Marchant, R. (2016). Relationship between on-farm trees stock and soil organic carbon along an altitudinal gradient, mount kilimanjaro, tanzania, *Forest Trees and Livelihood* .

Munson, B. R., Okiishi, T. H., Huebsch, W. W. and Rothmayer, A. P. (2013). *Fluid mechanics*, Wiley Singapore.

R Core Team (2018). *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria.
URL: *https://www.R-project.org/*

Renwick, M. E. (2001). Valuing water in a multiple-use system–irrigated agriculture and reservoir fisheries, *Irrigation and Drainage Systems* **15**(2): 149–171.

Salami, A., Kamara, A. B. and Brixiova, Z. (2010). *Smallholder agriculture in East Africa: Trends, constraints and opportunities*, African Development Bank Tunis.

Schibi, C. W. (2004). Plastic lined canal.

Soini, E. (2005). Land use change patterns and livelihood dynamics on the slopes of Mt. Kilimanjaro, Tanzania, *Agricultural Systems* **85**(3): 306–323.

Sokile, C. S., Kashaigili, J. J. and Kadigi, R. M. (2003). Towards an integrated water resource management in tanzania: the role of appropriate institutional framework in rufiji basin, *Physics and Chemistry of the Earth, Parts A/B/C* **28**(20): 1015–1023.

Spehn, E. M., Liberman, M. and Korner, C. (2006). *Land use change and mountain biodiversity*, CRC Press.

Tagseth, M. (2008). and the development of indigenous irrigation. methods and examples from kilimanjaro, tanzania., *Norsk Geografisk Tidsskrift - Norwegian Journal of Geograph* **14**(3).

Team, A. C. (2012). *Adobe Illustrator CS6 Classroom in a Book*, Adobe Press.

Tognetti, R., d'Andria, R., Lavini, A. and Morelli, G. (2006). The effect of deficit irrigation on crop yield and vegetative development of olea europaea l.(cvs. frantoio and leccino), *European journal of agronomy* **25**(4): 356–364.

Tripathi, N. and Bhattarya, S. (2004). Integrating indigenous knowledge and gis for participatory natural resource management: State-of-the-practice, *The electronic journal of information systems in developing countries* **17**(1): 1–13.

Turpie, J., Ngaga, Y. M. and Karanja, F. (2005). Catchment ecosystems and downstream water: the value of water resources in the pangani basin, tanzania, *Iucn water, nature and economics technical paper no. 7*, The World Conservation Union, Ecosystems and Livelihoods Group Asia.

Valipour, M. (2015). Future of agricultural water management in africa, *Archives of Agronomy and Soil Science* **61**(7): 907–927.

Vedeld, P., Liheuka, E. and Mbeyale, E. (2016). Institutional water resources management and livelihood adaptation: A case from kilombero rural areas, tanzania, *in* R. e. al (ed.), *Climate change and multi-dimensional sustainability in African agriculture*, Springer International Publishing.

Veldwisch, G., Beekman, P. and Bolding, J. (2013). Smallholder irrigators, water rights and investments in agriculture: Three cases from rural mozambique, *Water Alternatives* **6**(1): 125–141.

Villholth, K. G., Ganeshamoorthy, J., Rundblad, C. M. and Knudsen, T. S. (2013). Smallholder groundwater irrigation in sub-saharan africa: an interdisciplinary framework applied to the usangu plains, tanzania, *Hydrogeology Journal* **21**(7): 1481–1495.

Zech, M., Hörold, C., Leiber-Sauheitl, K., Kühnel, A., Hemp, A. and Zech, W. (2014). Buried black soils on the slopes of Mt. Kilimanjaro as a regional carbon storage hotspot, *CATENA* **112**: 125–130.

Chapter 4

Soil erosion under different farming systems in the southern slopes of Mt. Kilimanjaro

J. Kimaro [1,3*], A. Kolb [1], B. Huwe [1] and C. Bogner [2].
[1]Department of Soil Physics, University of Bayreuth, Bayreuth, Germany
[2]Ecosystem Research Group, Institute of Geography, Faculty of Mathematics and Natural Sciences, University of Cologne, Cologne, Germany,
[3]Tanzania Wildlife Research Institute, Tanzania

Manuscript in preparation.

Short title: Soil erosion in the slopes of Mt. Kilimanjaro

Abstract

Agriculture has been the main land use in the southern slope of Mt. Kilimanjaro for many decades. However, agroecosystems are increasingly exploited to meet increased food demand, which leads to loss of perennial vegetation covers and an increase in soil erosion. However, information about the actual causes and the extent of soil erosion therein is still rare. This hampers various committed efforts to implement sustainable solutions for soil management. We suppose that a combination of socio-ecological factors like local awareness of soil erosion, changes in agricultural practices, and soil properties, influence the occurrence of soil erosion in the mountain agroecosystem. Therefore, in this study, we determined (i) the extent of soil erosion under different farming systems and elevational gradient (ii) farmland cover change under different farming systems, and (iii) available local knowledge about soil management. Mixed approaches consisting of both quantitative and qualitative methodologies were used to collect data. Soil erosion was measured at six locations along an altitudinal gradient and stratified into two farming systems namely, maize, and agroforestry. In each farm plot, we measured run off, sediment loss, and rainfall. Additionally, major vegetation covers were analysed by using Google Earth-Pro aerial images. Community awareness about soil erosion was obtained through focus group discussions with participants from 6 villages and interviews with 10 key informants. We found that the difference in surface run-off and sediment loss was significant across elevational gradients and under the different farming systems ($p<0.05$). Run off measured -17.78 l, -21.18 l, and 13.37 l in the upper, mid and lower. Under the same order, sediment loss was -13.3g/m^2,-31.5g/m^2 and 40.03g/m^2. Rainfall increased significantly with elevation and was positively correlated with run off ($r > 0.5$). The perennial vegetation cover was dominant under agroforestry (>54%) while seasonal crops were dominant under the maize system (>75%). The smallest proportions of farmland covers were livestock fodder (< 9.07%) and settlement (<3.38%). Local awareness about indicators of soil erosion was significant between agroforestry and maize systems ($p < 0.05$). However, preferences towards less labor-intensive and cheaper soil conservation practices were significant across elevational gradients ($p < 0.05$). Revealing the relationship between agricultural land use and its vulnerability to soil erosion provides a useful input towards sustainable management of mountain agroecosystem.

Keywords: *Agroecosystem*, *Mt. Kilimanjaro*, *run off*, *sediment loss*, *soil properties*, *Rainfall.*

4.1 Introduction

For decades, tropical mountains have been important for agricultural production and supporting various ecological functions(Jodha, 2001; Thompson et al., 2007). Smallholder farming systems, applying different local knowledge of soil management, have been practised to meet domestic food supply and market demands of expanding human population (Mdoe et al., 2015; Soini, 2005; Barrera-Bassols and Zinck, 2003).

However, ongoing land-use changes in these areas are not sustainable, thus exposing soils to various forms of degradation. Conversion of farming systems, like removal of intermediate vegetation cover, alters canopy structure and therefore weaken the overall capacity of the farm to overcome rainfall erosion forces (Lal, 2017). The expansion of the monocropping system increases the proportion of exposed bare soil, while intensive use of mechanical tillage increases the risk of soil compaction (Altieri and Nicholls, 2017; Soini, 2005; Hamza and Anderson, 2005). Additionally, the introduction of new crops or agronomic practices could be incompatible with existing soil types, vegetation cover, hydrological processes, and nutrient circle (Demessie et al., 2012; Bernhard-Reversat, 2001).

Around the southern slopes of Mt. Kilimanjaro, expanding maize cultivation and uprooting of coffee plants is happening at the expense of agroforestry farms. This leads to loss of perennial farm vegetation cover, loss of native crops, and large exposure of bare soil (Lambrechts et al., 2002; Soini, 2005). Additionally, various traditional methods for soil conservation have been abandoned (Kimaro and Bogner, 2019). We suppose that ongoing land-use change in the slopes of Mt. Kilimanjaro could lead to increased soil erosion within the agroecosystems. However, there is no sufficient evidence to validate this claim.

In the present study, we are testing three hypotheses; (I) available local knowledge determine practices adopted (ii) farm land-use vary with farming systems (iii) extent of soil erosion depend on both elevational gradient and farming system. Therefore, we assessed available local knowledge about management of the soil in agroecosystems and compared the magnitude of soil erosion between the two dominant farming systems (maize and agroforestry) in the southern slope of Mt. Kilimanjaro. Specifically, the study determines; (i) available local knowledge on the management of soil erosion (ii) changes in farm vegetation cover between different farming systems and elevational gradient (iii) the extent of surface run off and sediment loss under different traditional farming systems and elevational gradient

Because agriculture has been practised on slopes of MtK̇ilimanjaro for many decades (Soini, 2005), this study expects high awareness about soil erosion among local farmers. Additionally, plots under agroforestry are expected to be less vulnerable to soil erosion because numerous higher trees and vegetation cover are retained (Jose, 2009). The findings of this study would enhance a better understanding of soil erosion patterns within mountain farming systems, which are often claimed but rarely quantified in tropical developing countries.

4.2 Materials and methods

4.2.1 Study area

The study was conducted on the southern slopes of Mt. Kilimanjaro (Figure 4.1) which is located between 2° 45′ and 3° 25′ S and 37° 0′ and 37° 45′ E), starting from the mountain foot (900 masl) up to the Kilimanjaro National Park boundary (submontane zone, 1600 masl). Three distinct land use types follow the altitudinal gradient. In the lower area, maize, monocropping, and extensive free livestock grazing are practised. In the mid-area (1200 – 1350 masl) the dominant farming system consists of coffee banana agroforestry and seasonal maize growing. In the upper area (1350 – 1600 m), agroforestry, in particular, traditional Chagga home gardens with banana and coffee crops are dominant (Hemp, 2006; O'Kting'ati and Kessy, 1991).

Two distinct rainy seasons occur in the study area. The long rains start from mid-March and continue until the end of May, while the short rains fall between October and December. Occasionally, short rains extend to the end of January of the following year. The driest period is from July to the end of September, while April and May are the wettest months. The mean annual average rainfall increases from 600 to 900 mm in the lower area to 1000 – 1200 mm in the mid-area and 1800 – 2000 mm in the upper area, respectively (Misana et al., 2012). The smallholder practices vary with elevation, whereby the mixed crop-livestock system is commonly practised in upper elevation zones while maize monocropping is done in the lower elevation zones. The soils in the study area originate mainly from volcanic material. In the upper areas of the cultivated zone, the main soil type is Leptosol (IUSS Working Group WRB, 2015), whereas in the plains Acrisols, Ferralsols, Lixisols, Nitisols, and Vertisols dominate (Zech et al., 2014).

4.2.2 Selection of study sites

Along elevational gradient, the study area was divided according to three major agro-ecological zones of cultivated areas of Mt. Kilimanjaro and stratified under two traditional farming systems namely; maize and agroforestry. Three villages were randomly selected from each farming system, thus make a total of six study villages, namely Kilanya, Foo, Uduru, Lyamungokati, Kimashuku, and Mailisita.

4.2.3 Collection of socio-economic information

Focus Group Discussion (FGDs) and Key Informants interviews (KIs) were used as the main tool to extract information from the community. Before the interviews, the purpose of the meetings was explained. Additionally, the informed-consent procedure was followed to ensure the participants about the confidentiality of their identities and their contributions (Krueger and Casey, 2014). FGDs involved meetings with local farmers regardless of their age, gender, wealth, and experience in farming. Others include community leaders and progressive farmers from six villages where the surveys were conducted. Between 15 and 20 participants attended each meeting. The aim of FGDs was to obtain local information on the following key topics; adoption of soil conservation practices,

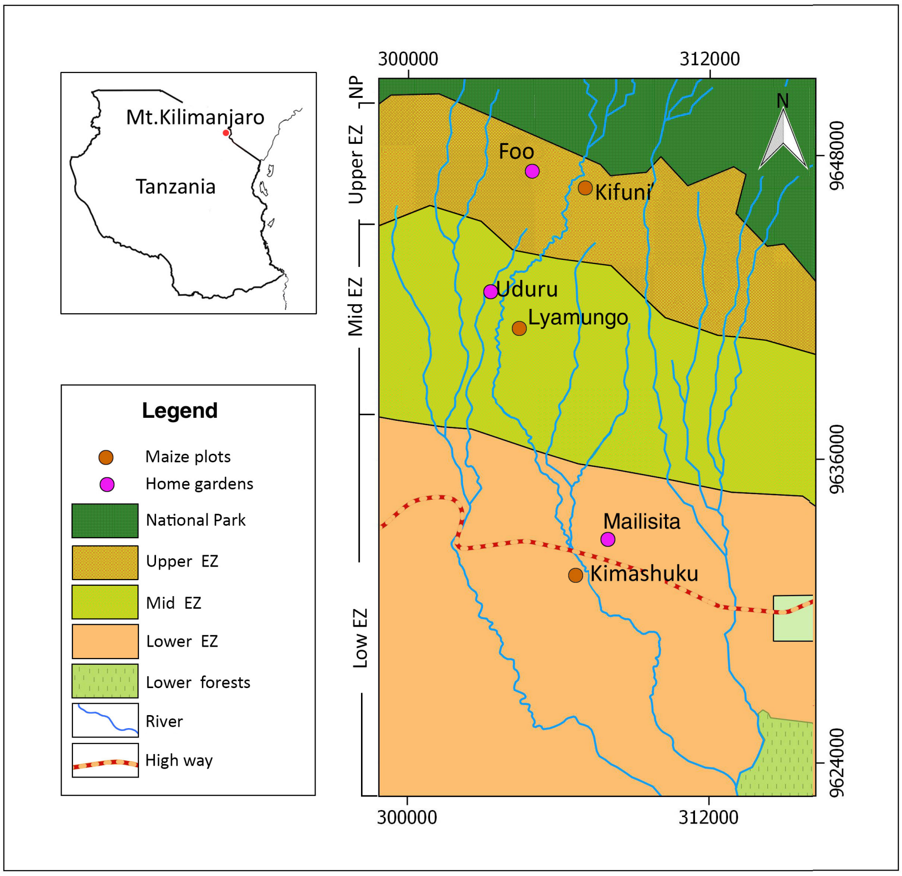

Figure 4.1: The study area (Google Maps, 2017), i.e., Southern slopes of Mt Kilimanjaro and its main vegetation zones (Hemp, 2006a; Hemp, 2006b; Misana et al., 2012a). Circles indicate plot locations dominated by two different agricultural management types i.e., maize (brown colour) and agroforestry (purple colour) systems.

knowledge on soil erosion indicators, relationships between local climate patterns, and farming practices. Key informant (n = 10-15) was conducted to obtain more detailed information that could not be obtained from FGDs. A guideline of the questions was used to lead discussions. All interviews were conducted in Kiswahili, but the responses were documented in English.

4.2.4 Assessment of farm vegetation cover

This exercise was conducted at plot level to quantify vegetation cover types and compare them between maize and agroforestry systems. A plot (1 ha size) was established in each village and their locations were recorded by using handheld GPS equipment (Garmin GPSMAP 64s). A recent aerial image of each plot was acquired from Google Earth Pro (GEP). This method has multiple advantages including, inexpensive measurement procedures, providing high-resolution images (up to 5 m from the ground), involves rapid and simple analysis (Taylor et al., 2011). Farm vegetation cover was delineated visually and classified distinctively (i) Perennial cover was composed of higher trees, banana, and coffee plants (ii) Seasonal cover was composed of areas used to grow seasonal crops, like maize and beans (iii) fodder plots involved patches of grown livestock pasture (iv) settlement cover involved built structures in the farms. Field visits were conducted for ground-truthing of all identified classes in the image.

4.2.5 Measurements of soil erosion in the field

This exercise was conducted in order to quantify the extent of soil erosion at the plot scale. Six erosion traps measuring 10 m in length and 3 m wide were installed in each study plot (Figure 4.2). The erosion plot was carefully delineated using joined cement blocks (30 cm high.) without disturbing the soil surface and the vegetation. At the lower part of the trap, a triangle shape covered by a plastic sheet channeled the run-off through a PVC pipe to a 150 l plastic barrel. Rainfall gauges were installed in the vicinity of each plot outside of trees and banana canopies. Since transport logistics could not allow us to attend erosion plots after every rainfall event, we scheduled our data collection exercise after every two days. Rainfall volume was measured by using a measuring cylinder, whereas the volume of run off was computed based on its height inside the barrel and the cross-sectional area of run off and the bottom of the barrel. The run-off mixture was vigorously stirred before the collection of 0.5 L sub-samples. Barrels were then cleaned up for the recording of the following run-off events. The collected samples were oven-dried at 110 C ° and reweighed until constant weight. Run off and rainfall data were recorded on a cumulative basis for the whole observation period.

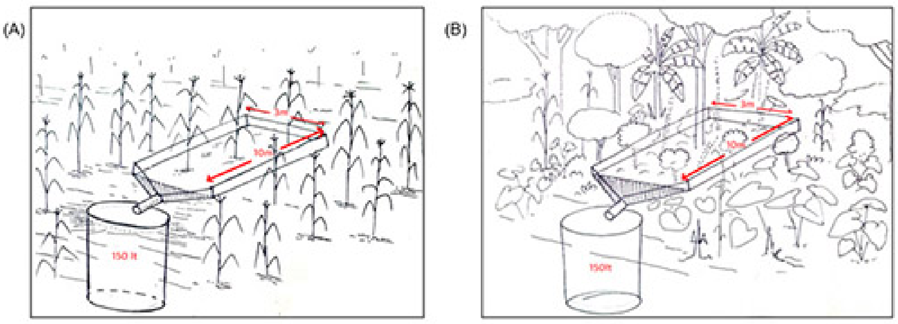

Figure 4.2: A sketch diagram showing set up of soil erosion traps under maize (A) and agroforestry farming systems, respectively (B)

4.2.6 Data analysis

Participatory agroforestry approach (Rocheleau and Rocheleau, 1985) was employed to classify soil conservation methods according to their types, effectiveness, and cost of establishment. The same approach was used to identify major types of soil erosion indicators that communities observe on their farm on a daily basis. Both qualitative and quantitative information collected during discussions were used to generate contextualized data that can be counted, ranked, and compared Ager et al. (2011).

Image from Google Earth was imported to Adobe Photoshop version CS 6S. To estimate the proportion of each cover type, the grids-making tool was used to mimic the function of traditional quadrant pantograph techniques (Hill, 1920). Grids of 3 mm^2 on the image presented a unit area of 4.3 m^2 on the farm.

The amount of rainfall, run off, and sediment loss was compared between maize and agroforestry systems and along the elevational gradient. Homogeneity of variance and Gaussian distribution of residuals were checked for each variable. Bootstrapping regression was used to determine variable estimates and confidence intervals (Efron and Tibshirani, 1986). Additionally, correlation analysis was employed to determine the relationship between rainfall and generated run off. All numerical variables were analysed by the R-statistical program (Core, 2012)..

4.3 Results

4.3.1 Local knowledge in soil conservation

Soil erosion control measures (SCMs) (Figure 4) differed significantly along an elevational gradient ($p < 0.05$), and were perceived differently among villagers. For example, vegetative propagated SCMs attracted 62% while those involved low investment costs were preferred by 75% of farmers.

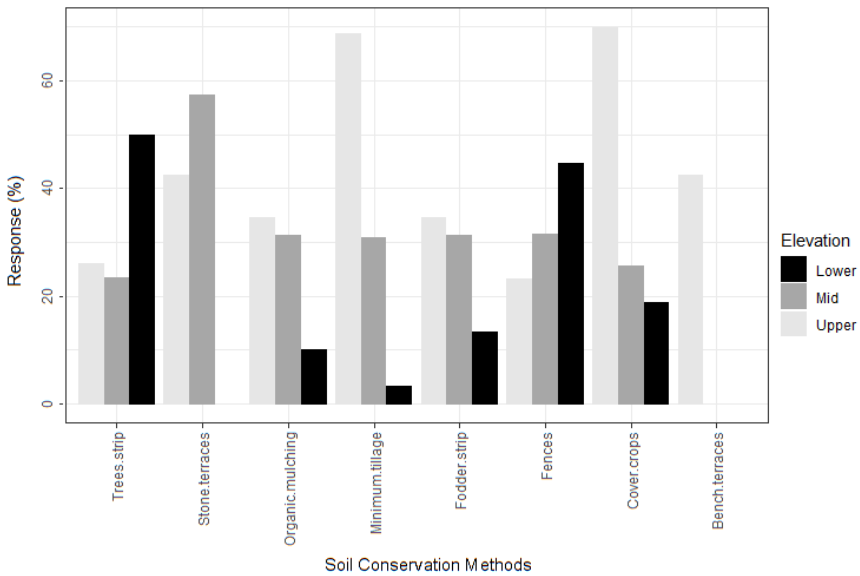

Figure 4.3: Common soil conservation measurements in the study area

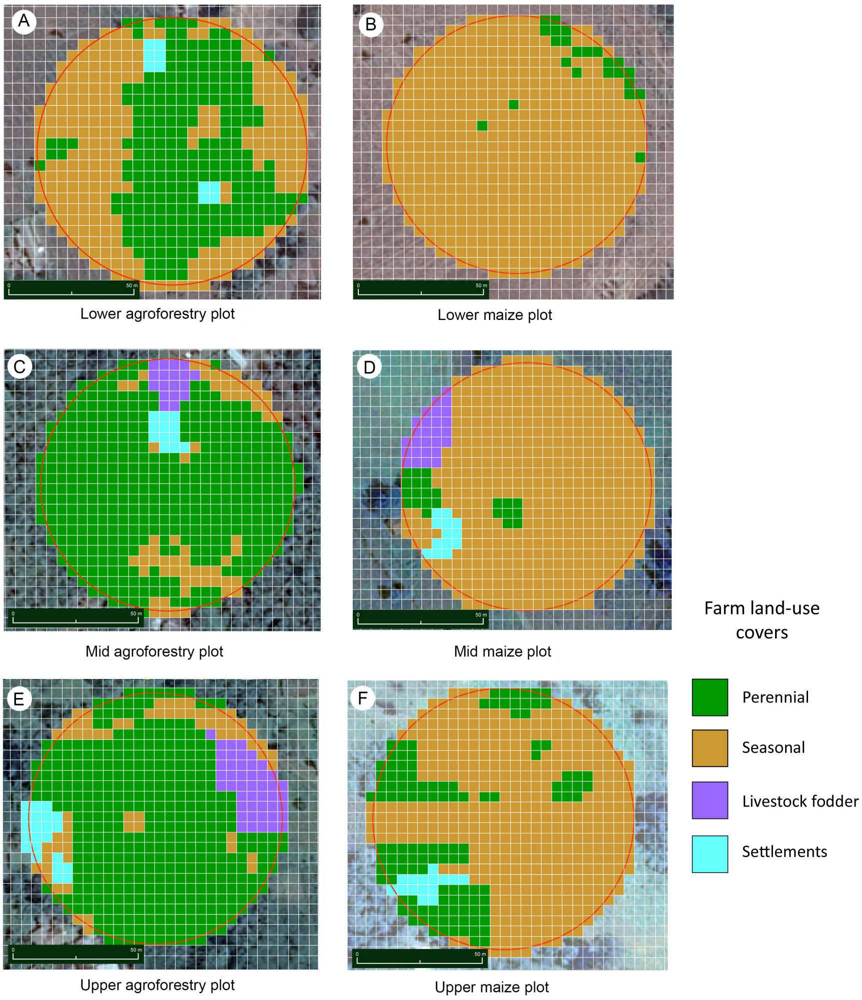

Figure 4.4: Land use and cover change under different farming systems and elevational gradient (Google Maps, 2017)

Soil erosion indicators did not differ significantly along elevational gradient ($p > 0.05$) as it was between maize and agroforestry ($p < 0.05$). The frequently reported indicators were rill channels (90%) followed by splash particles, sedimentation, and surface wash (60%). In the contrary, root exposure, rock exposure, and gullies were responded to by less than 50% of villagers. The landslide was only reported in the upper elevation zone.

Key informants reported that soil erosion indicators were developed from a combination of different factors. For example, the development of rill erosion, sheet-wash, and gullies was influenced by slope steepness, exposure of bare-land, and the amount of rainfall. Furthermore, bare soil, raindrops, and loose soil were perceived to cause splash erosion, root exposure, and rock exposure. Additionally, excessive rainfall, uncontrolled

Table 4.1: The proportion of land uses change (in percentage) along elevational gradient

Elevation	F.system	Settlement	Fodder	Perennial	Seasonal
Lower	Maize	0.00	0.00	3.59	96.41
	Agro	2.11	0.00	54.76	43.13
Mid	Maize	2.64	4.85	5.06	87.45
	Agro	2.53	3.38	83.54	10.55
Upper	Maize	2.95	0.00	21.73	75.32
	Agro	3.38	9.07	75.74	11.81

run off, and infertile soil were reported to cause landslides, broken terraces, and the development of gullies.

4.3.2 Changes in farm vegetation cover

Types and proportion of vegetation cover varied with an elevational gradient and between the two farming systems, (Figure 4.4, Table 4.1). Under the agroforestry, perennial vegetation cover was dominant, the highest being in the mid (83.5%) followed by the upper (75.7 %) while the least was in the lower elevation zone (54.8 %). The seasonal vegetation cover was dominant in the lower elevation zone (96.4 %) while the least was in the upper elevation zone (75.3 %). Livestock fodder plots and settlements areas indicated very small proportions ($> 10\%$). In the upper elevation zone fodder, patches constituted 9% and grown only under agroforestry. In the mid-elevation zone, a slight difference was observed between maize (4.85%) and agroforestry (3.38%). None of the farm plots in the lower elevation zone grew fodder. Nearly all surveyed plots, except maize plots in the lower area, established settlements that were less than 3.5%.

4.3.3 Soil erosion under different farming systems

Run off and sediment loss were relatively higher under maize system, with the maximum values measured in the lower elevation zones (Figure 4.5).

Run off decreased significantly in the mid and upper compared to the lower elevation zones (-21.2 l and -17.8 l, respectively) (Table 4.2). Additionally, run off increased significantly under maize compared to agroforestry (13.4 l). On the other hand, sediment loss decreased slightly different between the mid and upper elevation zones (-31.5 g and -31.3 g, respectively). Under the maize system, sediment loss increased by 13.4 g compared to agroforestry.

The relationship between rainfall and run off discharge was significant under different farming systems and along an elevational gradient ($p < 0.05$). Nearly 67% of study villages indicated more or less similar strength of the relationship ($r > 0.6$). This includes agroforestry lower, maize mid, and maize upper plots. Only maize lower and agroforestry upper indicated weak relationships ($r < 0.5$).

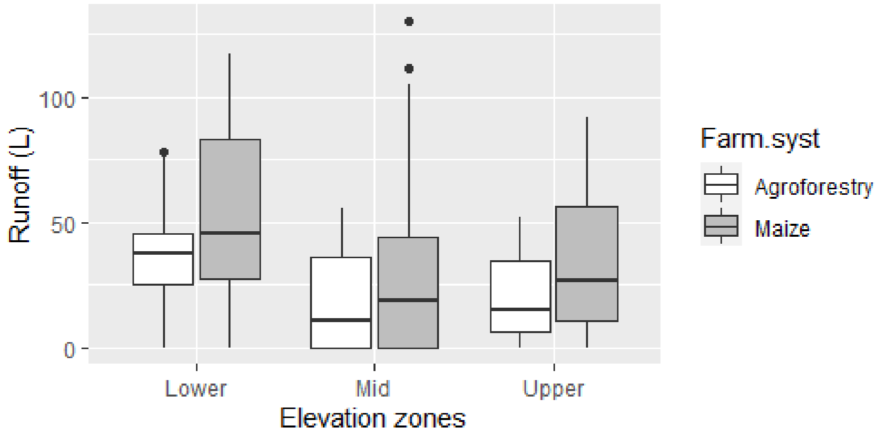

Figure 4.5: Spatial variation of run off along elevational gradient and across different farming systems

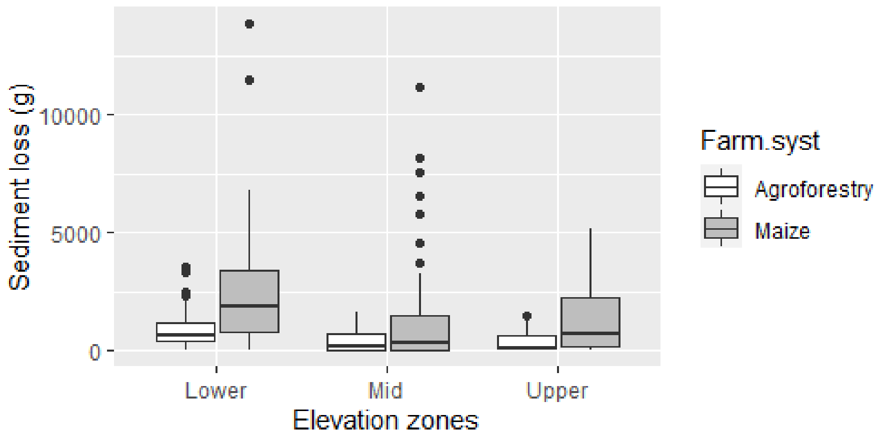

Figure 4.6: Spatial variation of sediment loss along elevational gradient and across different farming systems

Sediment loss in the lower elevation zone and under agroforestry measured 40.03 g/m^2 and the difference was significant. The amount generated under maize increased by 41.8 g/m^2 than agroforestry and was significant. In the mid and upper elevation zones, sediment loss decreased by nearly 31.5 g/m^2, but was only significant in the upper elevation zone.

Table 4.2: Model summary of dynamics of run off and sediment loss across elevational gradient and different farming systems

Model parameters				
Variable	Intercept (Property in low elevation and agroforestry	Mid elevation	Upper elevation	Maize system
run off (L)	38.46	-21.18	-17.78	13.37
	(32.3, 45.32)	(-30.12,-12.88)	(-26.04,-10.16)	(6.82,20.39)
Sediment loss (g)	40.03	-31.5	-31.3	41.7
	(27.5,57.8)	(-57,-13.27)	(-55.2,-14.2)	(28.1,57.2)

4.4 Discussion

4.4.1 Soil erosion practices in agroecosystem

Variability of SCM along elevation could be related to different degrees of soil erosion risks. Because the upper elevation zone of the study area receives higher and frequent rains Hemp (2006), and is characterized by steep slopes Kimaro et al. (2019), adoption of efficient SCM, like terraces and growing higher trees is inevitable. In similar locations, like the slopes of Mt. Kenya and the high-lands of Ethiopia, bench and stone terraces have been widely constructed Bishaw (2001). In the lower elevation zone of the study area, topography could have less influence on run off. Thus, simple structures like strip grass and boundary trees could be sufficient.

However, a higher preference towards cheaper SCM tells that majority of villagers could be experiencing financial difficulties. Like many other rural people in Tanzania, villagers around Mt. Kilimanjaro experience low household income Kangalawe et al. (2014). According to key informants, investment in the construction of stone or bench terraces demands a lot of money in terms of purchasing material and hiring skilled labour. This implies that the number of established terraces in the upper elevation zone of the study area could be far less than was supposed to be.

Increased community's preference towards vegetation-based SCMs, like trees, live fences, and fodder strips could be due to expanding the size of roots and shoot over time which enhances plants' efficiency in controlling soil erosion. Likewise, farm trees and other plants have multiple benefits to the household Jose (2009). It is also suggested that establishing vegetation-based SCM could demand less physical labour compared to terraces. Social factors like decreasing number of young people in rural areas of Mt. Kilimanjaro Kangalawe et al. (2014) could be among key drivers.

Broad knowledge about soil erosion indicators among many villagers is an indication that communities around Mt. Kilimanjaro have accumulated experiences in the management of soil erosion in their farms. Probably, this is related to the long history of agricultural activities on slopes of Mt.Kilimanjaro Soini (2005); Winter (1994). In the central highlands of Kenya, a study has indicated that farmers' local knowledge can be used to describe soil erosion indicators and explanation of their causes Okoba and

De Graaff (2005).

The difference in soil erosion indicators between farming systems suggests that the adopted management practices could influence changes in soil properties. Thus, soil functions, like control of surface run off, particle detachment, and transport Dilshad et al. (1996) were reported more under the maize compared to the agroforestry system. This implies that farms that indicated a large number of soil erosion indicators could be more vulnerable to soil erosion risks. Therefore, farmers should apply a combination of different soil conservation approaches in the daily operation of their farms.

4.4.2 Changes in farm vegetation cover and its implications to soil conservation

The observed changes in farm vegetation cover in the study area suggest that farm trees and adopted crops are very sensitive to both biophysical and management factors. High organic matter soil (Kimaro et al., 2019), and frequent precipitation (Røhr and Killingtveit, 2003; Hemp, 2006) in the upper elevation zone of Mt. Kilimanjaro could be favorable environmental conditions for most trees species and crop varieties. Owing to that, agroforestry farms in the upper elevation zone could be characterized by an assemblage of higher trees, banana, and coffee plants. These multi-canopy structures break raindrops before reaching the soil surface, thus reducing kinetic energy that could cause soil particle detachment and displacement Lal (2017).

A large proportion of livestock fodder cover is found in the upper elevation zone. This could be related to the dominance of zero-grazing practices. Our observations concur with previous studies that reported integration of fodder patches in agroecosystem as a source of feed to stall-kept livestock in upper slopes of Mt. Kilimanjaro Soini (2005). However, an area covered by livestock fodder indicated only a small proportion of the total farm vegetation cover. Probably, its contribution to soil conservation could be relatively lower compared to perennial cover. However, a small rate of soil erosion could be noticed when a large part of the farm is covered by livestock fodder Nunes et al. (2011). Being cover plants, livestock fodder can potentially reduce the speed of run-off water and trap a large proportion of loose sediments Lal (2017).

The seasonal cover type was dominant in the lower elevation area. All farm plots under seasonal cover types could experience higher rates of soil compared to perennial cover types. Because this type of canopy cover is very porous, a large proportion of raindrops could reach the bare soil with fewer restrictions Lal (2017), thus can cause massive soil loss. Although farmers have a tendency of integrating bean crops with maize, the effectiveness of beans in controlling soil erosion is relatively weaker compared to other leguminous crops like cowpea Lal (2017). This implies that there is a need for further research to identify other associated crops or farming systems that can efficiently control surface run off or sediment transport from maize plots.

4.4.3 Run off and sediment loss patterns

The observed patterns of surface run off and sediment loss in the study plots confirm that these two processes correlate positively to each in the study area. However, the higher rates of surface run off and sediment loss in the lower elevation zone could be related to poor management of the soil and vegetation cover. This study found that simple SCMs, like contour bounds and fodder strips, were dominant in the lower elevation zone. The same applies to a large number of gullies and sediment deposits which reveal the occurrence of massive soil loss.

We suggest that farm activities involved in growing maize plants could be the major factor that promotes massive soil loss in the lower elevation zone. Based on our discussions with key informants, we noted that farmers practice delayed sawing because the majority of them rely on rain-fed farming. According to them, this timing enhances seed germination a few days after starting rainfall. Also, being a strategy to avoid loss of seeds from being eaten by birds or soil fauna in case seeds will stay in the soil for a long time. Based on these speculations, it could take a number of weeks before maize leaves develop into a full canopy. Because long rains are highly intense around Mt. Kilimanjaro Røhr and Killingtveit (2003), raindrops could be reaching the soil surface with very high kinetic energy and cause massive displacement of soil particles Yan et al. (2018); Lal (2017).

On the other hand, lower rates of run off and sediment loss under agroforestry could be due to the dominance of perennial vegetation cover and the existence of multi-canopy. This configuration offers strong protection against the impacts of raindrops and limits the transport of suspended materials Lal (2017). Moreover, a slight difference in soil erosion between agroforestry plots in the mid and upper elevation zones reveals high homogeneity in terms of controlling soil erosion. This is attributed to the dominance of higher trees, banana crops, and coffee plants within farms Soini (2005); O'Kting'ati and Kessy (1991).

A weak correlation between rainfall and surface run off under agroforestry plots was expected. Although recorded rainfall was highest in the upper elevation zone, its influence on run off generation could be suppressed by the large volume of organic litter and cover plants. Thus, a large proportion of rainfall could be infiltrated into the ground. In contrast, a weak correlation between rainfall and surface run off under maize plot in the lower elevation zone is surprising. Because soils in the lower elevation zones are clay-rich, and often compacted Kimaro et al. (2019), only a little amount of rainfall could be lost through infiltration. Probably, preferential flow paths like rotten steam and rodent holes lead to the loss of a certain amount of rainfall.

4.5 Conclusions and Recommendations

An understanding of soil erosion patterns in slopes of Mt. Kilimanjaro is critically important to an explanation of soil management under small-holder farming in mountain regions. A mismatch between high community awareness on soil erosion and the low adoption of soil conservation measures suggested that most local farmers in the study area have abandoned traditional practices for sustainable soil management. A study has revealed that maize monocropping is not a suitable farming system in the mountain regions, thus compatible crops or shrubs could be integrated with maize to reduced extreme soil erosion rates. Taping local knowledge about soil erosion and conducting regular field measurements could be useful in identifying critically degraded areas in the agroecosystem and recommending appropriate conservation measures.

Bibliography

Ager, A., Stark, L., Sparling, T. and Ager, W. (2011). Rapid appraisal in humanitarian emergencies using participatory ranking methodology (prm), *New York, NY: Program on Forced Migration and Health, Columbia University Mailman School of Public Health* .

Altieri, M. A. and Nicholls, C. I. (2017). The adaptation and mitigation potential of traditional agriculture in a changing climate, *Climatic Change* **140**(1): 33–45.

Barrera-Bassols, N. and Zinck, J. A. (2003). Ethnopedology: a worldwide view on the soil knowledge of local people, *Geoderma* **111**(3-4): 171–195.

Bernhard-Reversat, F. (2001). *Effect of exotic tree plantations on plant diversity and biological soil fertility in the Congo savanna: with special reference to eucalypts*, Cifor.

Bishaw, B. (2001). Deforestation and land degradation in the ethiopian highlands: a strategy for physical recovery, *Northeast African Studies* pp. 7–25.

Core, R. (2012). Team. 2020, *R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www. R-project. org/. Accesado octubre* .

Demessie, A., Singh, B. R., Lal, R. and Børresen, T. (2012). Effects of eucalyptus and coniferous plantations on soil properties in gambo district, southern ethiopia, *Acta Agriculturae Scandinavica, Section B-Soil & Plant Science* **62**(5): 455–466.

Dilshad, M., Motha, J. and Peel, L. (1996). Surface runoff, soil and nutrient losses from farming systems in the australian semi-arid tropics, *Australian Journal of Experimental Agriculture* **36**(8): 1003–1012.

Efron, B. and Tibshirani, R. (1986). Bootstrap methods for standard errors, confidence intervals, and other measures of statistical accuracy, *Statistical science* pp. 54–75.

Hamza, M. and Anderson, W. (2005). Soil compaction in cropping systems: A review of the nature, causes and possible solutions, *Soil and tillage research* **82**(2): 121–145.

Hemp, A. (2006). Ecology and altitudinal zonation of pteridophytes on mt. kilimanjaro, *African Plants: Biodiversity, Ecology, Phytogeography and Taxonomy* .

Hill, R. R. (1920). Charting quadrats with a pantograph, *Ecology* **1**(4): 270–273.

IUSS Working Group WRB (2015). *World Reference Base for Soil Resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps*, World Soil Resources Reports No. 106. FAO, Rome.

Jodha, N. (2001). Sustainable agriculture in fragile resource zones: technological imperatives, *in* N. Jodha (ed.), *Life on the Edge: Sustaining Agriculture and Community Resources in Fragile Environments*, Oxford University Press, New Delhi.

Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: an overview, *Agroforestry systems* **76**(1): 1–10.

Kangalawe, R., Noe, C., Tungaraza, F., Naiman, G. and Mlele, M. (2014). Understanding of traditional knowledge and indigenous institutions on sustainable land management in kilimanjaro region, tanzania, *Open Journal of soil Science* **4**: 469–493.

Kimaro, J. and Bogner, C. (2019). Water management under traditional farming systems: Practices and limitations of the mfongo system around mt. kilimanjaro.

Kimaro, J. G., Scharsich, V., Huwe, B. and Bogner, C. (2019). Distribution of traditional irrigation canals and their discharge dynamics at the southern slopes of mount kilimanjaro, *Frontiers in Environmental Science* **7**: 24.

Krueger, R. A. and Casey, M. A. (2014). *Focus groups: A practical guide for applied research*, Sage publications.

Lal, R. (2017). Soil erosion by wind and water: problems and prospects, *Soil erosion research methods*, Routledge, pp. 1–10.

Lambrechts, C., Woodley, B., Hemp, A., Hemp, C., Nnyiti, P. et al. (2002). Aerial survey of the threats to mt. kilimanjaro forests, *Technical report*, United Nations Development Programme (UNDP).

Mdoe, N. S., Mlay, G. I. and Kadigi, M. L. (2015). Farming systems in tanzania: Empirical evidence of changes in livelihood patterns and poverty among smallholder farmers, *Sustainable Intensification to Advance Food Security and Enhance Climate Resilience in Africa*, Springer, pp. 555–571.

Misana, S. B., Sokoni, C. and Mbonile, M. J. (2012). Land-use/cover changes and their drivers on the slopes of mount kilimanjaro, tanzania, *Journal of geography and Regional Planning* **5**(8): 151.

Nunes, A. N., De Almeida, A. C. and Coelho, C. O. (2011). Impacts of land use and cover type on runoff and soil erosion in a marginal area of portugal, *Applied Geography* **31**(2): 687–699.

Okoba, B. O. and De Graaff, J. (2005). Farmers' knowledge and perceptions of soil erosion and conservation measures in the central highlands, kenya, *Land Degradation & Development* **16**(5): 475–487.

O'Kting'ati, A. and Kessy, J. (1991). The farming systems on mount kilimanjaro, *The Conservation of Mount Kilimanjaro. IUCN, Gland and Cambridge* pp. 71–80.

Rocheleau, D. E. and Rocheleau, D. (1985). *Land use planning with rural farm households and communities: participatory agroforestry research*, International Council for Research in Agroforestry Nairobi, Kenya.

Røhr, P. C. and Killingtveit, Å. (2003). Rainfall distribution on the slopes of mt kilimanjaro, *Hydrological sciences journal* **48**(1): 65–77.

Soini, E. (2005). Land use change patterns and livelihood dynamics on the slopes of Mt. Kilimanjaro, Tanzania, *Agricultural Systems* **85**(3): 306–323.

Taylor, B. T., Fernando, P., Bauman, A. E., Williamson, A., Craig, J. C. and Redman, S. (2011). Measuring the quality of public open space using google earth, *American journal of preventive medicine* **40**(2): 105–112.

Thompson, J., Hodgkin, T., Atta-Krah, K., Jarvis, D., Hoogendoorn, C. and Padulosi, S. (2007). Biodiversity in agroecosystems, *Farming with nature: the science and practice of ecoagriculture* .

Winter, C. J. (1994). Some problems of chagga identity, *Sprachen und Sprachzeugnisse in Afrika: Eine Sammlung Philologischer Beiträge Wilhelm JG Möhlig zum* **60**: 459–471.

Yan, Y., Dai, Q., Yuan, Y., Peng, X., Zhao, L. and Yang, J. (2018). Effects of rainfall intensity on runoff and sediment yields on bare slopes in a karst area, sw china, *Geoderma* **330**: 30–40.

Zech, M., Hörold, C., Leiber-Sauheitl, K., Kühnel, A., Hemp, A. and Zech, W. (2014). Buried black soils on the slopes of mt. kilimanjaro as a regional carbon storage hotspot, *Catena* **112**: 125–130.

Chapter 5

Variability of soil properties under different farming systems on Mt. Kilimanjaro in Tanzania

J. Kimaro [1,4*], A. Treydte [2], B. Huwe [1] and C. Bogner [3].
[1]Department of Soil Physics, University of Bayreuth, Bayreuth, Germany
[2]Nelson Mandela African Institution of Science and Technology, Tanzania
[3]Ecosystem Research Group, Institute of Geography, Faculty of Mathematics and Natural Sciences, University of Cologne, Cologne, Germany
[4]Tanzania Wildlife Research Institute, Tanzania

Manuscript in preparation.

Short title: Variability of soil properties on Mt. Kilimanjaro.

Abstract

The agroecosystems at the southern slope of Mt. Kilimanjaro provide several ecosystem services, in particular food production. However, agricultural land-use change threatens their future sustainability and increases land degradation. Low awareness about the actual cause and extent of the problem among local farmers, and extension officers could be a major driving factor, thus limiting decision options on the selection of appropriate adaptation measures. We compared the variability of soil properties in different farming systems, namely agroforestry and maize, along the southern slopes of Mt. Kilimanjaro, Tanzania. We measured soil C, N, P, soil texture, bulk density, and the cation exchange capacity (CEC) and base saturation in 24 plots across three major agro-ecological zones, mainly related to elevation. We analysed the data with a linear model based on bootsrapping and principal component analysis. Our results show that sand content increased while clay content and bulk density decreased with increasing elevation The C content was slightly lower in maize compared to agroforestry (-0.88%), but not N and P. Soil C and N contents increased in the upper compared to the lower elevation zones (3.8% and 0.3%, respectively), while P decreased by 19 mg kg^{-1}. The content of exchangeable bases showed a heterogeneous picture. The largest difference was the decrease of Ca and Mg in the upper elevation zone compared to the lower elevation (-1191 mg kg^{-1} and -458 mg kg^{-1}, respectively). A total of four principal components (PCs) explained 81% of the variance in the dataset. Overlaps between farming systems and elevational zones in each PC reveal a resemblance of soil properties across different study plots. We conclude that some villages could be more vulnerable to food insecurity based only on their location, and they will require more efforts to improve soil quality than others. We suggest the use of soil quality indicators, such as soil nutrients, can assist both farmers and extension officers in achieving sustainable agricultural production.

Keywords: *Farming systems*, *Soil nutrients*, *Farmers*, *Crops production*, *Heterogeneity*, *Elevational gradient.*

5.1 Introduction

Changes in farming systems and management practices influence the variability of soil properties. Monitoring these changes based on soil quality indicators (SQIs) enables a better understanding of soils and ecosystem management Doran and Parkin (1994); Karlen et al. (1997); Shukla et al. (2006). Chemical soil properties, particularly essential nutrients for plants, and soil moisture are important for plant physiological growth and yield production Cavagnaro (2016); Uchida (2000). Soil physical properties, such as bulk density and texture, determine the extent of root penetration, root architecture, and water uptake Colombi et al. (2018). Additionally, soil organic matter improves soil aggregate stability and water infiltration Boyle et al. (1989); Mamedov et al. (2017). The framework for soil quality assessment suggests important variables for each particular soil function and depends on society goals, and their threshold values should be considered carefully Arshad and Martin (2002).

Along the elevational gradient of Mt. Kilimanjaro, different farming systems have been adopted by local farmers. Maize monocropping, coffee-banana, and traditional home gardens are dominant in the lower, mid, and upper agroecological zones, respectively Soini (2005b); O'Kting'ati and Kessy (1991). However, the current management of the agroecosystems around Mt. Kilimanjaro threatens its capacity to sustain optimal food production and other ecological functions. Increased agricultural intensification responds to the shrinking of arable land and growing food demands Soini (2005a). Shifts towards seasonal crops at the expense of perennial vegetation followed changes in market demands and community preferences Maghimbi (2007). Expanding maize cultivation has intensified mechanization in land preparation Soini (2005b). Studies have indicated that unsustainable management of agroecosystem affect some soil ecological processes and can lead to soil degradation Mitchard and Flintrop (2013); Bishaw (2001). We suppose that the current management of the agroecosystem around Mt. Kilimanjaro could lead to changes in soil properties, like increasing bulk density, loss of essential nutrients, and exchangeable bases in the agroecosystem. However, there is no sufficient empirical evidence to validate this claim.

In the present study, we are testing two hypotheses. Firstly, changes in management practices affect soil properties in an agroecosystem. Secondly, variations in soil properties indicate a clear separation between farming systems and elevational gradients. Therefore, we analysed soil properties across areas of different agricultural land use and identified indicators that explain the variability across the three major agro-ecological zones of Mt. Kilimanjaro, namely the lower, mid, and upper elevation zones. Specifically, this study seeks to understand the following: (i) the effect of increasing elevational gradient and changing farming practices on soil properties (ii) variations of soil quality in the agroecosystem.

Because of inherent soil-landscape and human-induced variability under smallholder systems Tittonell et al. (2013), this study expects that soil properties could vary or show overlaps between farm plots of different farming systems or elevational zones in agroecosystems around Mt. Kilimanjaro. The findings of this study could contribute to several local efforts to sustain crop production, reduce economic losses and improve ecological resilience on smallholder farms.

5.2 Materials and methods

5.2.1 Study area

The study area was located on the southern slopes of Mt. Kilimanjaro (2°45'–3°25'S and 37°00'–36°43'E; (Figure 5.1). At the mountain foothills, the colline zone starts around 900 masl (meter above sea level) up to the submontane zone (1600–1800 masl) [@Hemp2011]. It includes three distinct agro-ecological zones: the lower area (< 1100 masl) is extensively used for maize mono-cropping and pastoral livestock grazing, the mid-elevation zone (1200–1350 masl) is dominated by coffee-banana agroforestry in combination with maize and the upper area (1350–1600 masl) is dominated by traditional “Chagga home gardens”, including food crops mixed with perennial tree species and zero-grazing livestock Fernandes et al. (1985); Soini (2005b). The area receives bimodal rainfall, with short rains in October–December and long ones in mid-March–May Hemp (2006). The mean annual rainfall ranges from 600–900 mm in the lower area, 1000–1200 mm in the mid-elevation area to 1800–2000 mm in the upper area, respectively Røhr and Killingtveit (2003). The landscape is mainly dominated by volcanic soils, i.e., in the upper areas, one finds mainly Leptosols Borrelli et al. (2017); IUSS Working Group WRB (2015), whereas in the plains mainly Vertisols, Ferralsols, and Nitisols Zech et al. (2014).

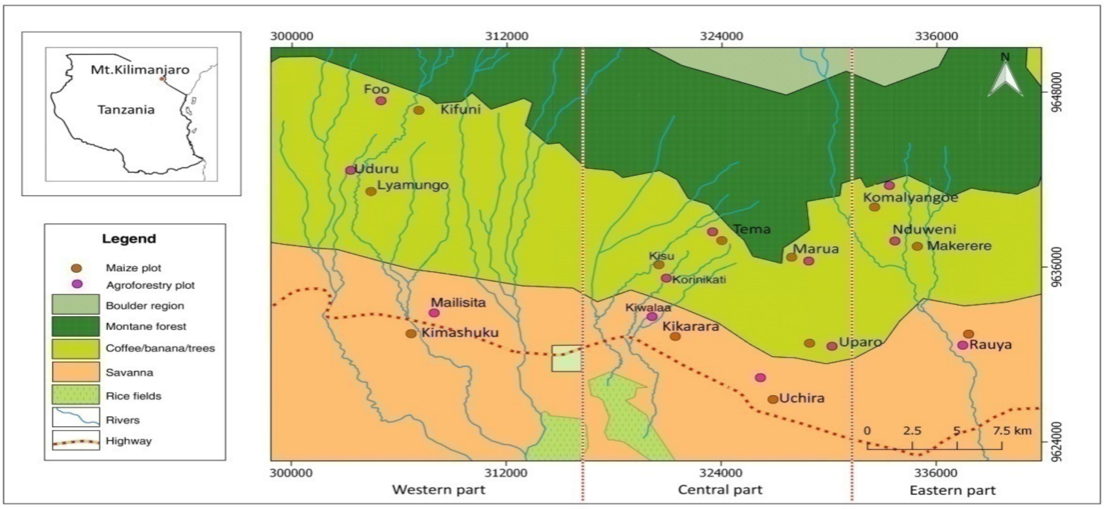

Figure 5.1: The study area (based on Google Maps, 2017), i.e., Southern slopes of Mt. Kilimanjaro and its main vegetation zones (Hemp, 2006). Circles indicate plot locations dominated by two different agricultural management types, i.e.
maize (brown in colour) and agroforestry (purple in colour) systems."

Several agricultural land uses were identified through field visits and informal meetings with a selected group of farmers ($n = 10$) who have good knowledge about the farming system in the area. The cropping history, duration, and management practices were identified and discussed within the team. Only farming system types that have been traditionally practised by local people for food production were selected. Thus, maize mono-cropping and agroforestry were finally selected as the main farming systems under assessment. Moreover, identification of major agroecological zones characterizing the study area was based on the available literature, particularly published papers and books about the agroecosystem of Mt. Kilimanjaro O’Kting’ati and Kessy (1991); Hemp (2006).

5.2.2 Soil sampling

We established 24 sampling plots (1 ha large) across the entire study area (Figure 5.1) based on the Land Degradation Surveillance Framework (LDSF) Vågen et al. (2010). They were located in the two major traditional farming systems, namely 12 in agroforestry and 12 in maize farming, respectively. To compare findings along the mountain elevation gradient, the sampling plots were organized in four transects running from the lower (900 masl) to the upper area (1600 masl)

5.2.3 Soil physical properties

We measured soil texture as a proxy indicator for water permeability, vulnerability to erosion, and root growth Passioura (2002). Additionally, we assessed soil bulk density (BD) and soil water content to determine the effect of tillage on soil structure and water storage in surface soil. We collected 300 g of bulk soil samples from the top 30 cm soil in each subplot. Samples were air-dried and sieved < 2 mm. Organic matter (OM) was removed by hydrogen peroxide in a hot water bath. The sand was determined by wet sieving Carter and Gregorich (2008) and fractions of clay, silt, and fine sand by sedimentation using PARIO equipment Durner et al. (2017). BD was determined on undisturbed soil cores collected at a depth of 30 cm by weighing them before and after drying to constant weight at 105 °C Heuscher et al. (2005). The volumetric soil water content (VWC) was determined by multiplying the gravimetric water content by the bulk density.

5.2.4 Soil chemical properties

We selected five essential plant nutrients to assess their availability in the soil, namely nitrogen (N), phosphorus (P), calcium (Ca), magnesium (Mg), potassium (K), and the beneficial element sodium (Na). Although not a plant nutrient, Na benefits crop growth, but can also degrade soil structure when an excessive amount is accumulated in the soil Rengasamy and Olsson (1991). Mountain climatic gradients influence the unequal distribution of soluble salts, with higher concentrations accumulating at the foot of the mountain Tsui et al. (2004). Additionally, we measured the effective cation exchange capacity (CEC_{eff}) and base saturation (CEC_{bsat}) for all samples. Total soil N was determined with a CHN analyser (Thermo Quest, Flash EA, 1112 model) Jimenez and Ladha (1993). Available P was first extracted by using Calcium-Acetate-Lactate (CAL) van Laak et al. (2018) and then its concentration was measured by inductively coupled plasma optical emission spectroscopy (ICP-OES, Varian Vista Pro model, Varian Inc., The Netherlands) Maguire and Sims (2002). Additionally, all exchangeable cations (Mg, Na, K, and Ca) were extracted with ammonium chloride solution, and their concentrations were measured by ICP-OES König et al. (2005).

5.2.5 Data analysis

Soil properties were compared between the two major farming systems (maize and agroforestry) and along the elevational gradient. To estimate the differences between the farming systems and along the elevation, we fitted linear models with elevation zones and farming systems as parameters. Because the model residuals were not normally distributed, we used the bootstrap to calculated confidence intervals Efron and Tibshirani (1986). Indeed, the bootstrap does not rely on normally distributed residuals. We intentionally do not rely on statistical tests because they only give dichotomous yes-no answers instead of effect-size estimations Ho et al. (2019). We bootstrapped the data, 10000 times in a stratified way (e.g., respecting the number of samples in each farming system and elevation) and re-calculated the linear models. Confidence intervals for model parameters were estimated based on the student-t method Davison and Hinkley (1997). Note that OM and VWC were not modelled. Instead of OM, we preferred to analyse C and N contents. VWC was not modelled because it changes too rapidly and is affected by precipitation.

To analyse soil properties responsible for variations in the dataset, we calculated a principal component analysis (PCA) Andrews and Carroll (2001). The eigenvalue greater than 1 was retained to determine the number of principal components (PCs) that explained total variation in the dataset Rezaei et al. (2006). All calculations were done in R Core (2012).

5.3 Results

5.3.1 Soil physical and chemical properties

In the following, we only comment on properties that differed significantly, i.e., where the bootstrap confidence intervals did not include zero. All results are displayed in Table 5.1 and Table 5.2. The sand content increased with elevation, while clay content and BD decreased ((Figure 5.2) and Table 5.1). Additionally, BD was larger under the maize farming system. The VWC was not modelled, however, the data showed an increase with elevation in maize, larger values, and a larger variability under agroforestry (Figure 5.3)..

The contents of C and N increased in the upper compared to the lower elevation zone (3.76% and 0.34%, respectively), while P decreased (-19.3 mg kg^{-1}). C was slightly lower under maize compared to agroforestry (-0.88%) (Figure 5.4)(Table 5.2).

Variation of exchangeable cations were very heterogeneous in the study area (Figure 5.5). Ca and Mg decreased by a substantial amount in the upper compared to the lower elevation zones (-1191 mg/kg and -458 mg kg^{-1}, respectively). Similarly, K and Mg decreased in the mid-elevation zone (-342 mg kg^{-1} and -196.3 mg kg^{-1}, respectively) and Mg decreased under maize (-180 mg kg^{-1}) compared to agroforestry (Table 5.2). CEC_{eff} and CEC_{bsat} decreased in the upper elevation compared to the lower elevation (-0.09 mmolc g^{-1} and -0.14, respectively) (Figure 5.6 and Table 5.2).

Table 5.1: Modelling results of soil physical properties under different farming systems and elevation. Numbers in parentheses show the lower and the upper confidence intervals.

Soil property	Intercept	Maize	Mid elevation	Upper elevation
Sand	8.57	-0.05	6.53	15.38
	(6.12, 10.82)	(-3.4, 3.59)	(2.99, 9.91)	(11.26,19.98)
Silt	29.29	23	3.35	-11.92
	(22.78, 36.32)	(-4.2, 9.2)	(-5.97, 11.66)	(-19.92, -4.47)
Clay	47.18	-0.27	-12.31	-18
	(39.48, 54.69)	(-9.6, 8.58)	(-22.13, -1.63)	(-28.69, -6.92)
BD	1.02	0.1	-0.08	-0.33
	(0.97, 1.06)	(0.04, 0.17)	(-0.16, -0.01)	(-0.4, -0.25)

Table 5.2: Modelling results of soil chemical properties under different farming systems and elevation. Numbers in parentheses show the lower and the upper confidence intervals.

Soil property	Intercept	Mid elevation	Upper elevation	Maize
C	2.53	-0.88	0.47	3.76
	(1.88, 3.18)	(-1.77, -0.02)	(-0.28, 1.18)	(2.51, 4.99)
N	0.21	-0.07	0.05	0.34
	(0.15, 0.28)	(-0.15, 0)	(-0.01, 0.12)	(0.23, 0.44)
P	34.73	1.8	-5.8	-19.31
	(16.36, 59.25)	(-16.88, 24.35)	(-35.76, 22.76)	(-44.33, -1.16)
K	508.75	71.91	-341.96	-157.88
	(79.41, 785.28)	(-183.96, 546.79	-652.89,-73.12)	(-509.71,493.93)
Ca	2858	-395.47	-371.2	-1191.34
	(2291.32,3355.44	(-922.52,224.82	(-1020.14,262.14	(-1839.07,-456.09)
Mg	796.64	-180.04	-196.34	-458
	(673.08,916.58)	(-302.62,-47.87	(-352.25,-37.85	(-591.96, -306.58)
Na	16.19	2.81	-3.37	2.91
	(10.11, 20.52)	(-3.08, 11.66)	(-7.67, 1.04)	(-5.26, 17.12)
CEC_{eff}	0.22	-0.03	-0.04	-0.09
	0.18, 0.25)	(-0.07, 0.01)	(-0.08, 0)	(-0.14, -0.03)
CEC_{bsat}	1.02	-0.04	-0.03	-0.14
	(0.99, 1.06)	(-0.12, 0.02)	(-0.06, 0.01)	(-0.26, -0.07)

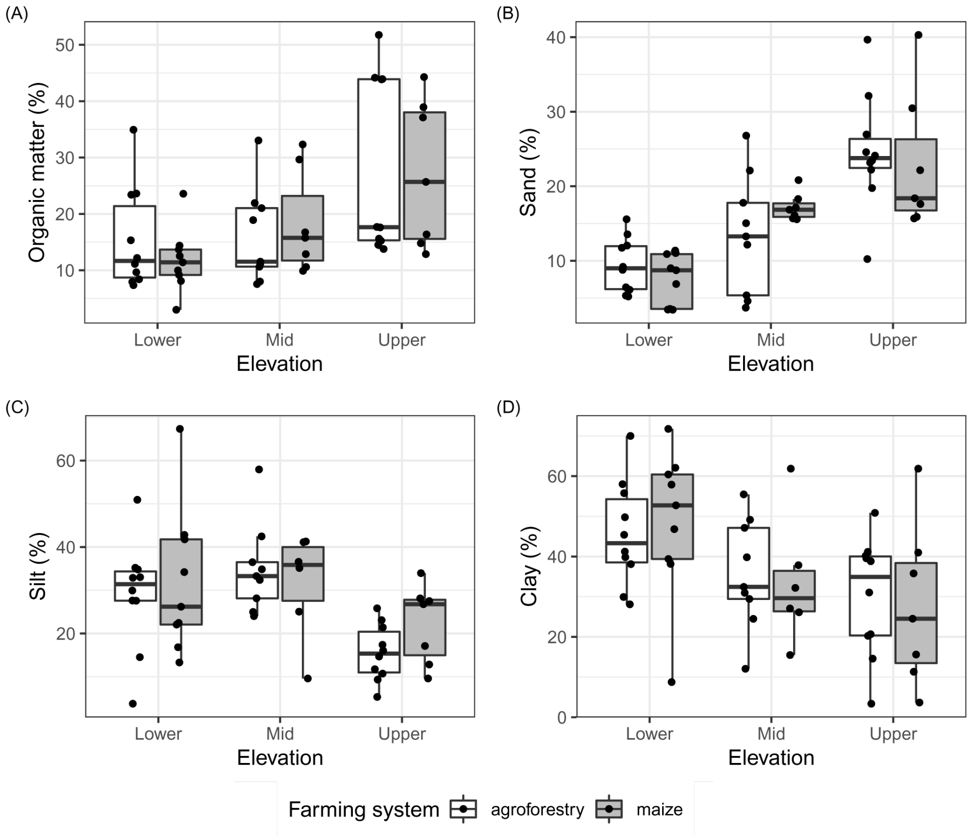

Figure 5.2: Variability of soil organic matter and texture across elevation and farming systems: (A) organic matter, (B) sand content (C) silt content (D) clay content. Lower, mid and upper represent major agroecological zones.

5.3.2 Variations of soil quality

The first four principal components (PCs) explained 81% of the variance in the dataset. Bi-plots confirmed a certain degree of overlap between farming systems and elevational zones under each PC (Figure 5.7) (Figure 5.8).

PC1 accounted for 41% of variance in the data set and had negative loadings from N, C, and sand, positive loadings from exchangeable cations (Ca, Mg, and K), and pH. We suggest that PC1 explains variations of essential plant nutrients in the dataset. It is mostly associated with the lower and mid-elevations (Figure 5.8)). PC2 explained 19% of variance in the dataset. It showed positive loadings from clay and BD. We suggest that PC2 explains the variation of soil compaction in the data set. The PC3 and PC4 accounted for the smallest proportions of explained variance in the dataset (11% and 10.8%, respectively). PC3 has strong positive loadings from sand and silt and negative from clay. It could be related to variations of soil permeability in the dataset. PC4 has a strong negative loading from Na and a strong positive loading from silt. There is no

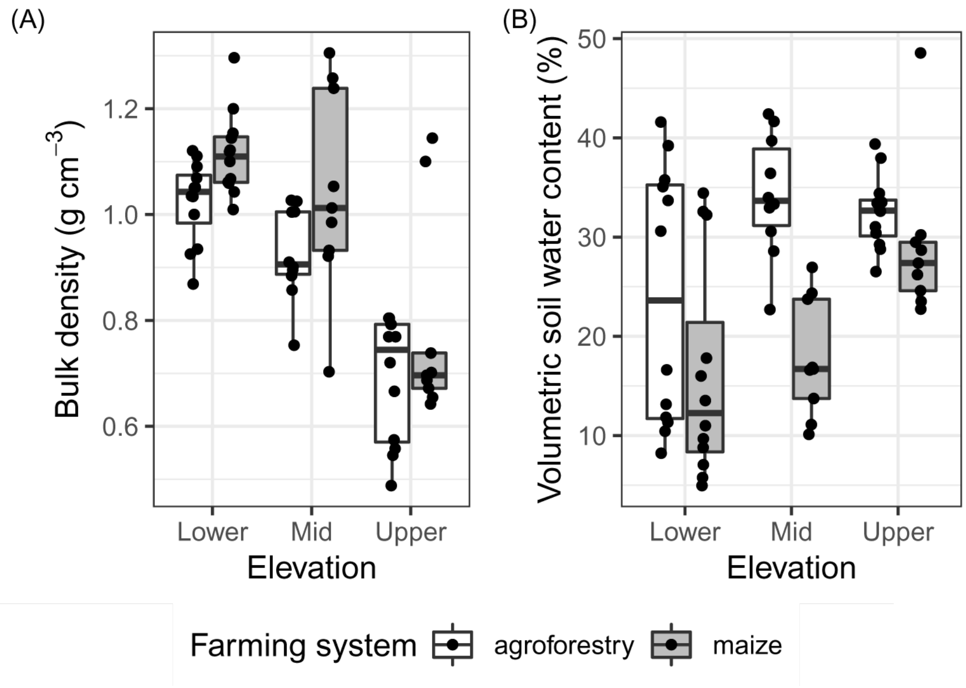

Figure 5.3: Spatial distribution of (A) soil bulk density (B) and volumetric water content along the elevational gradient. Lower, mid and upper represent major agroecological zones.

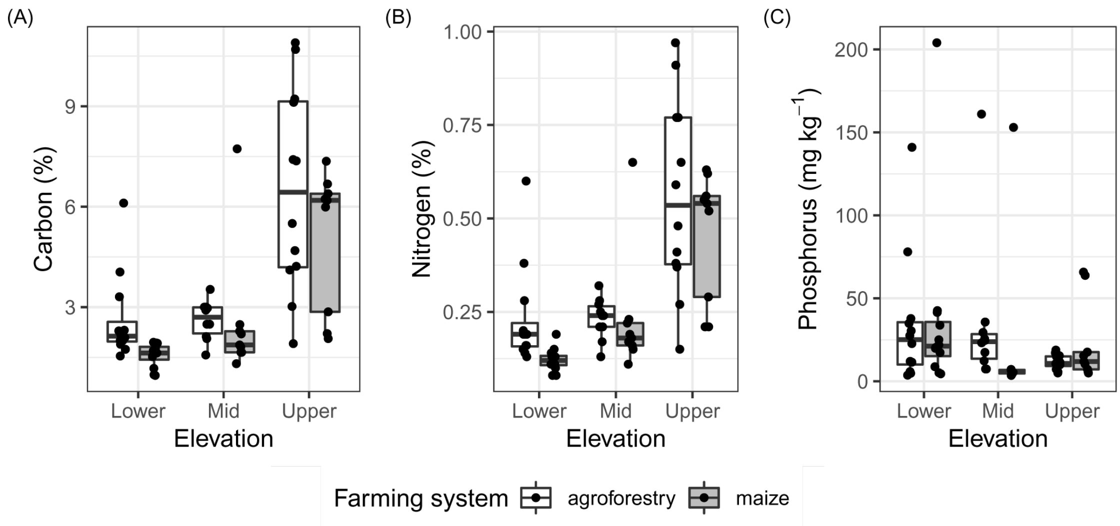

Figure 5.4: Variation of (A) carbon, (B) nitrogen and (C) phosphorus along the elevational gradient. Lower, mid and upper represent major agroecological zones.

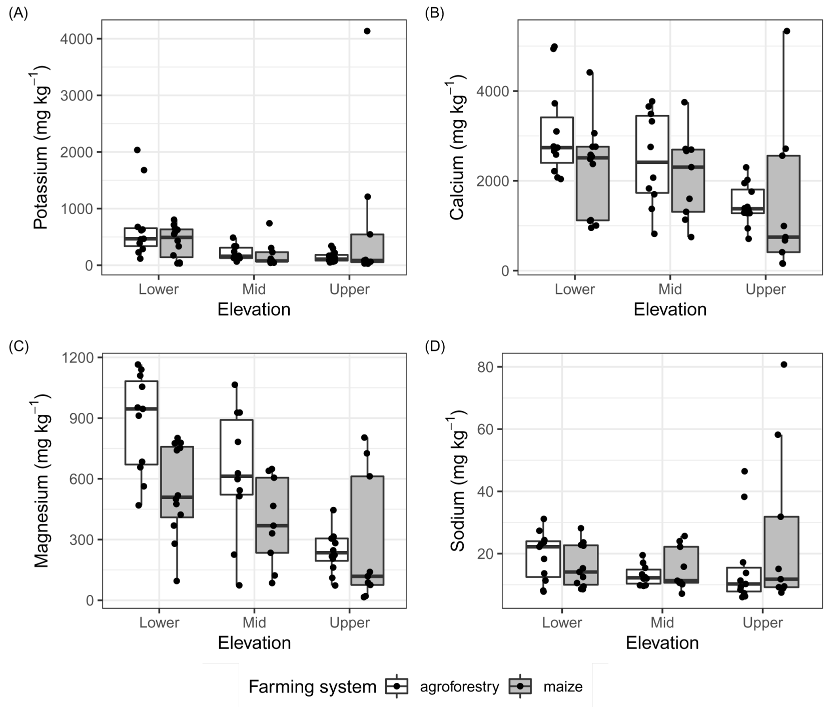

Figure 5.5: Variation of exchangeable bases along the elevational gradient. (A) potassium, (B) calcium (C) magnesium and (D) sodium. Lower, mid and upper represent major agroecological zones.

sufficient evidence that the increase in Na content is influenced by changes in the farming systems. Thus, this PC is probably related to a few unusual data points.

5.4 Discussion

5.4.1 Differences in soil properties across the two agroecosystem types

The contents of sand, silt, and clay did not differ significantly between the two farming systems because the parental material could be homogeneous across the slope. Additionally, being static in nature (Carter and Gregorich, 2008), soil textural properties could not be altered by ongoing management practices. On the other hand, changes of sand, silts, and clay contents along the elevational gradient of the mountain were expected due to the geomorphological process (Buol et al., 2011). Our observations concur with findings from previous studies conducted around the cultivated area of Mt. Kilimanjaro reporting increased sand content in the upper elevation zones (Kimaro et al., 2019), while clay-rich soils like Vertisols and Acrisols were found in the plains (Zech et al., 2014).

Soil BD and VWC could be sensitive to changes in farm management practices. Under maize, deep tillage was observed during our field visit. This practice could cause

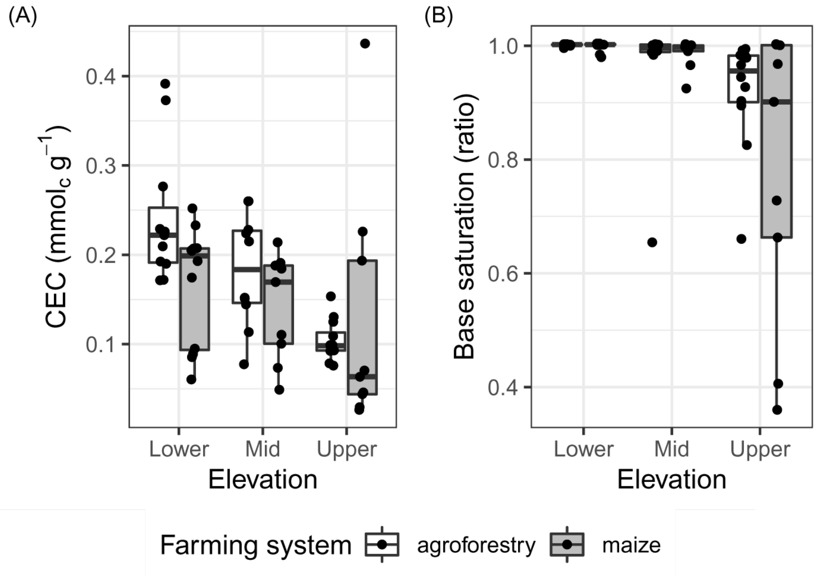

Figure 5.6: Variation of (A) CEC and (B) base saturation along the elevational gradient. Lower, mid and upper represent major agroecological zones.

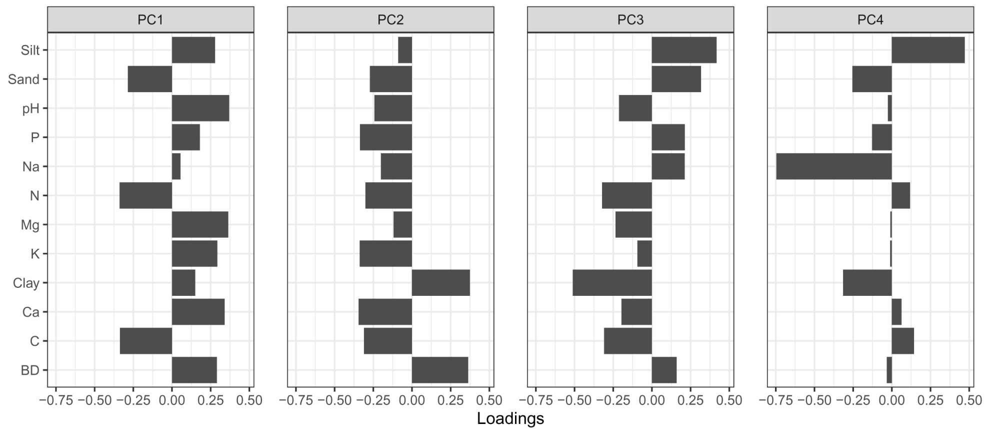

Figure 5.7: PCA loadings

considerable degradation of soil structure. Because of a thin canopy under maize farming, bare soil is exposed to precipitation. Erosion, but also sealing and crusting of the soil surface, could be the consequences (Hamza and Anderson, 2005). Although the observed value of soil BD under maize is below the critical limit for root penetration (Udom and Ehilegbu, 2018), the associated level of soil compaction could accelerate water run-off and poor nutrients' distribution (Shah et al., 2017).

A slight difference of C and N contents between maize and agroforestry is surprising. Following high crop diversity and good soil management practices under agroforestry,

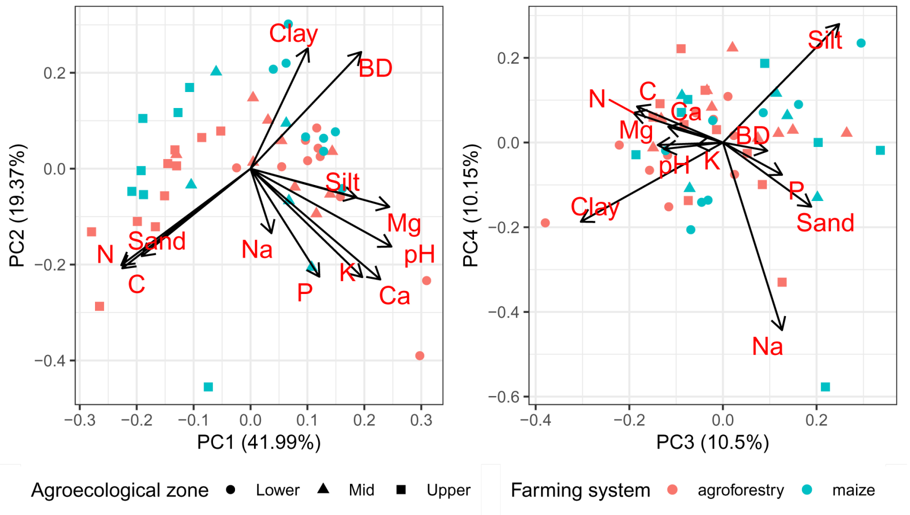

Figure 5.8: Results of the PCA analysis

their soils are known to retain higher content of soil C and N (Querné et al., 2017; Muchane et al., 2020; Jose, 2009). Probably, the ongoing management of agroforestry farms in the study area does not favour the accumulation of soil organic carbon. This could be due to shrinking the intermediate and lower vegetation cover (Soini, 2005b), thus less amount of organic litter is available. Additionally, native farm vegetation cover is being replaced by diverse exotic tree species (Maghimbi, 2007). Introduction of some non-native trees in agroforestry farms causes the decline of soil fertility (Demessie et al., 2012). However, our data set is relatively small and shows a large variability. Accordingly, the estimated difference of C and N contents between agroforestry and maize ranges between -1.77% and -0.02% and -0.15% and 0%, respectively. The largest variability in the data was measured in the upper elevation zone, and we cannot exclude an interaction effect between the farming system and the elevation. The size of our data set does not allow for the estimation of interaction effects.

The decreased soil P content in the upper elevation zone could be related to patterns of climatic gradient and parent material of the soil. Being sand-rich, soils in the upper elevation zone could have high P buffering capacity (Frossard et al., 1992). Additionally, the high soil moisture content in the upper elevation zone influences adsorption of P (Sun et al., 2020). Therefore, the smaller amount of soil P in the upper elevation zone is probably less related to management practices.

The decrease of exchangeable Mg and Ca in the upper elevation zone be related to low soil clay content. The number of negative surface charges increases with the increasing content of clay in the soil, thus attracting and holding a large number of positively charged ions (Hartemink, 2016). However, lower exchangeable Mg under maize compared to agroforestry could be the effect of poor management of soil organic matter. Since the level of soil C content correlates to soil OM, maize plots could retain less quantity of exchangeable cations.

Heterogeneous changes in soil exchangeable cations imply that the use of soluble inorganic fertilizers needs high precaution measures in the upper and mid-elevation zones. They are known to influence economic loss among smallholder farmers and cause environmental pollution (Masmoudi et al., 2020). Therefore, we advocate the use of composite or green manure to improve soil CEC in these locations. Being cheaply available, the use of organic manure could be affordable to the majority of local farmers Holt-Giménez (2008).

5.4.2 Differences of SQI and their implications in the agroecosystem

The assessment of four principal components (PCs) has revealed that the largest variability in the data set is due to the elevation and there is little separation of data points depending on the farming system. Because of that, the overlap between farming systems or elevation gradients exists in variable degrees. In PC1, for example, increasing C and N in the upper elevation zone suggests that the traditional home gardens (O'Kting'ati and Kessy, 1991) could be distinct compared to other agroforestry practices in the mid and lower elevation zones. Variations in PC2 could indicate soil compaction where soil mechanical stress is not carefully monitored. Because clay soil is dominant in the lower elevation zone, soils under both maize and agroforestry could be vulnerable to increasing BD. Increased mechanical stress like mechanized tillage is known to cause soil compaction in crop fields (Hamza and Anderson, 2005). Changes in soil particle size, as explained in PC3, suggest that soils in the upper and mid-elevation zones are more permeable, thus could minimize surface run-off and be appropriate for the production of root crops (Lal et al., 1994; Colombi et al., 2018). Information indicated by PC4 suggests that the increase of Na in the upper elevation zone could be strongly influenced by underlying parental material rather than management activities. This is the only variable in the dataset that indicated high distinctiveness to other variables.

5.5 Conclusions

An understanding of soil properties and their relationship to the cultivated area of Mt. Kilimanjaro is pivotal to an explanation of soil quality management under small-holder farming in mountain regions. The study has demonstrated that soils in the agroecosystem of Mt. Kilimanjaro differ in soil properties, which implies that crop yield and quality could be higher in some plots than others. Therefore, some farmers could face more difficulties in addressing food security challenges or have to invest more efforts to improve soil quality. The use of soil quality indicators could benefit both farmers and extension officers as a decision-making tool to identify suitable locations for crops, achieve precise use of production inputs and manipulate crop calendars.

Bibliography

Andrews, S. S. and Carroll, C. R. (2001). Designing a soil quality assessment tool for sustainable agroecosystem management, *Ecological Applications* **11**(6): 1573–1585.

Arshad, M. A. and Martin, S. (2002). Identifying critical limits for soil quality indicators in agro-ecosystems, *Agriculture, Ecosystems & Environment* **88**(2): 153–160.

Bishaw, B. (2001). Deforestation and land degradation in the ethiopian highlands: a strategy for physical recovery, *Northeast African Studies* pp. 7–25.

Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V. et al. (2017). An assessment of the global impact of 21st century land use change on soil erosion, *Nature communications* **8**(1): 2013.

Boyle, M., Frankenberger Jr, W. and Stolzy, L. (1989). The influence of organic matter on soil aggregation and water infiltration, *Journal of production agriculture* **2**(4): 290–299.

Buol, S. W., Southard, R. J., Graham, R. C. and McDaniel, P. A. (2011). *Soil genesis and classification*, John Wiley & Sons.

Carter, M. and Gregorich, E. (2008). Soil sampling and methods of analysis. 2nd, *Can. Soc. Soil Sci* **1224**.

Cavagnaro, T. R. (2016). Soil moisture legacy effects: impacts on soil nutrients, plants and mycorrhizal responsiveness, *Soil Biology and Biochemistry* **95**: 173–179.

Colombi, T., Torres, L. C., Walter, A. and Keller, T. (2018). Feedbacks between soil penetration resistance, root architecture and water uptake limit water accessibility and crop growth–a vicious circle, *Science of the total environment* **626**: 1026–1035.

Core, R. (2012). Team. 2020, *R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www. R-project. org/. Accesado octubre* .

Davison, A. C. and Hinkley, D. V. (1997). *Bootstrap Methods and Their Application*, Cambridge Series in Statistical and Probabilistic Mathematics, Cambridge University Press, Cambridge.

Demessie, A., Singh, B. R., Lal, R. and Børresen, T. (2012). Effects of eucalyptus and coniferous plantations on soil properties in gambo district, southern ethiopia, *Acta Agriculturae Scandinavica, Section B-Soil & Plant Science* **62**(5): 455–466.

Doran, J. W. and Parkin, T. B. (1994). Defining and assessing soil quality, *Defining soil quality for a sustainable environment* **35**: 1–21.

Durner, W., Iden, S. C. and von Unold, G. (2017). The integral suspension pressure method (isp) for precise particle-size analysis by gravitational sedimentation, *Water Resources Research* **53**(1): 33–48.

Efron, B. and Tibshirani, R. (1986). Bootstrap methods for standard errors, confidence intervals, and other measures of statistical accuracy, *Statistical science* pp. 54–75.

Fernandes, E. C., Oktingati, A. and Maghembe, J. (1985). The chagga homegardens: a multistoried agroforestry cropping system on mt. kilimanjaro (northern tanzania), *Agroforestry systems* **2**(2): 73–86.

Frossard, E., Fardeau, J., Ognalaga, M. and Morel, J.-L. (1992). Influences of agricultural practices, soil properties and parent material on the phosphate buffering capacity of cultivated soils developed in temperate climates, *European Journal of Agronomy* **1**(1): 45–50.

Hamza, M. and Anderson, W. (2005). Soil compaction in cropping systems: A review of the nature, causes and possible solutions, *Soil and tillage research* **82**(2): 121–145.

Hartemink, A. E. (2016). Scheffer/schachtschabel soil science., *Soil Science Society of America Journal* **80**(2): 528–528.

Hemp, A. (2006). Ecology and altitudinal zonation of pteridophytes on mt. kilimanjaro, *African Plants: Biodiversity, Ecology, Phytogeography and Taxonomy* .

Heuscher, S. A., Brandt, C. C. and Jardine, P. M. (2005). Using soil physical and chemical properties to estimate bulk density, *Soil Science Society of America Journal* **69**(1): 51–56.

Ho, J., Tumkaya, T., Aryal, S., Choi, H. and Claridge-Chang, A. (2019). Moving beyond P values: Data analysis with estimation graphics, **16**: 565–566.

Holt-Giménez, E. (2008). Out of agra: The green revolution returns to africa, *Development* **51**(4): 464–471.

IUSS Working Group WRB (2015). *World Reference Base for Soil Resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps*, World Soil Resources Reports No. 106. FAO, Rome.

Jimenez, R. and Ladha, J. (1993). Automated elemental analysis: A rapid and reliable but expensive measurement of total carbon and nitrogen in plant and soil samples, *Communications in Soil Science and Plant Analysis* **24**(15-16): 1897–1924.

Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: an overview, *Agroforestry systems* **76**(1): 1–10.

Karlen, D., Mausbach, M. J., Doran, J., Cline, R., Harris, R. and Schuman, G. (1997). Soil quality: a concept, definition, and framework for evaluation (a guest editorial), *Soil Science Society of America Journal* **61**(1): 4–10.

Kimaro, J. G., Scharsich, V., Huwe, B. and Bogner, C. (2019). Distribution of traditional irrigation canals and their discharge dynamics at the southern slopes of mount kilimanjaro, *Frontiers in Environmental Science* **7**: 24.

König, N., Blum, U., Symossek, F., Bussian, B., Ellinghaus, R., Furtmann, K., Gärtner, A., Gutwasser, F., Hauenstein, M. and Kiesling, G. (2005). Handbuch forstliche analytik, *Gessellschaft für Analytik. Bonn: Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft* .

Lal, R. et al. (1994). *Soil erosion research methods*, CRC Press.

Maghimbi, S. (2007). Recent changes in crop patterns in the kilimanjaro region of tanzania: the decline of coffee and the rise of maize and rice, *African study monographs* **35**: 73–83.

Maguire, R. O. and Sims, J. T. (2002). Measuring agronomic and environmental soil phosphorus saturation and predicting phosphorus leaching with mehlich 3, *Soil Science Society of America Journal* **66**(6): 2033–2039.

Mamedov, A. I., Huang, C.-h., Aliev, F. A. and Levy, G. J. (2017). Aggregate stability and water retention near saturation characteristics as affected by soil texture, aggregate size and polyacrylamide application, *Land Degradation & Development* **28**(2): 543–552.

Masmoudi, S., Magdich, S., Rigane, H., Medhioub, K., Rebai, A. and Ammar, E. (2020). Effects of compost and manure application rate on the soil physico-chemical layers properties and plant productivity, *Waste and Biomass Valorization* **11**(5): 1883–1894.

Mitchard, E. T. and Flintrop, C. M. (2013). Woody encroachment and forest degradation in sub-saharan africa's woodlands and savannas 1982–2006, *Philosophical Transactions of the Royal Society B: Biological Sciences* **368**(1625): 20120406.

Muchane, M. N., Sileshi, G. W., Gripenberg, S., Jonsson, M., Pumariño, L. and Barrios, E. (2020). Agroforestry boosts soil health in the humid and sub-humid tropics: A meta-analysis, *Agriculture, Ecosystems & Environment* **295**: 106899.

O'Kting'ati, A. and Kessy, J. (1991). The farming systems on mount kilimanjaro, *The Conservation of Mount Kilimanjaro. IUCN, Gland and Cambridge* pp. 71–80.

Passioura, J. (2002). Soil conditions and plant growth, *Plant, Cell & Environment* **25**(2): 311–318.

Querné, A., Battie-laclau, P., Dufour, L., Wery, J. and Dupraz, C. (2017). Effects of walnut trees on biological nitrogen fixation and yield of intercropped alfalfa in a mediterranean agroforestry system, *European Journal of Agronomy* **84**: 35–46.

Rengasamy, P. and Olsson, K. (1991). Sodicity and soil structure, *Soil Research* **29**(6): 935–952.

Rezaei, S. A., Gilkes, R. J. and Andrews, S. S. (2006). A minimum data set for assessing soil quality in rangelands, *Geoderma* **136**(1-2): 229–234.

Røhr, P. C. and Killingtveit, Å. (2003). Rainfall distribution on the slopes of mt kilimanjaro, *Hydrological sciences journal* **48**(1): 65–77.

Shah, A. N., Tanveer, M., Shahzad, B., Yang, G., Fahad, S., Ali, S., Bukhari, M. A., Tung, S. A., Hafeez, A. and Souliyanonh, B. (2017). Soil compaction effects on soil health and cropproductivity: an overview, *Environmental Science and Pollution Research* **24**(11): 10056–10067.

Shukla, M., Lal, R. and Ebinger, M. (2006). Determining soil quality indicators by factor analysis, *Soil and Tillage Research* **87**(2): 194–204.

Soini, E. (2005a). Changing livelihoods on the slopes of Mt. Kilimanjaro, Tanzania: Challenges and opportunities in the Chagga homegarden system.

Soini, E. (2005b). Land use change patterns and livelihood dynamics on the slopes of Mt. Kilimanjaro, Tanzania, *Agricultural Systems* **85**(3): 306–323.

Sun, F., Song, C., Wang, M., Lai, D. Y., Tariq, A., Zeng, F., Zhong, Q., Wang, F., Li, Z. and Peng, C. (2020). Long-term increase in rainfall decreases soil organic phosphorus decomposition in tropical forests, *Soil Biology and Biochemistry* **151**: 108056.

Tittonell, P., Muriuki, A., Klapwijk, C., Shepherd, K. D., Coe, R. and Vanlauwe, B. (2013). Soil heterogeneity and soil fertility gradients in smallholder farms of the east african highlands, *Soil Science Society of America Journal* **77**(2): 525–538.

Tsui, C.-C., Chen, Z.-S. and Hsieh, C.-F. (2004). Relationships between soil properties and slope position in a lowland rain forest of southern taiwan, *Geoderma* **123**(1-2): 131–142.

Uchida, R. (2000). Essential nutrients for plant growth: nutrient functions and deficiency symptoms, *Plant nutrient management in Hawaii's soils* pp. 31–55.

Udom, B. E. and Ehilegbu, J. (2018). Critical moisture content, bulk density relationships and compaction of cultivated and uncultivated soils in the humid tropics, *Asian Soil Research Journal* pp. 1–9.

Vågen, T., Shepherd, K. D., Walsh, M. G., Winowiecki, L., Desta, L. T. and Tondoh, J. E. (2010). Afsis technical specifications: soil health surveillance, *Africa Soil Information Service (AfSIS). Nairobi, Kenya: World Agroforestry Centre* .

van Laak, M., Klingenberg, U., Peiter, E., Reitz, T., Zimmer, D. and Buczko, U. (2018). The equivalence of the calcium-acetate-lactate and double-lactate extraction methods to assess soil phosphorus fertility, *Journal of Plant Nutrition and Soil Science* **181**(5): 795–801.

Zech, M., Hörold, C., Leiber-Sauheitl, K., Kühnel, A., Hemp, A. and Zech, W. (2014). Buried black soils on the slopes of mt. kilimanjaro as a regional carbon storage hotspot, *Catena* **112**: 125–130.

LIST OF PUBLICATIONS

List of peer reviewed journal papers

Included in this thesis

1. Kimaro, Jerome Gadi, Valeska Scharsich, Bernd Huwe, and Christina Bogner. "Distribution of traditional irrigation canals and their discharge dynamics at the southern slopes of Mount Kilimanjaro."Frontiers in Environmental Science-7 (2019): 24.
2. Kimaro, J., and C. Bogner. Water management under traditional farming systems: Practices and limitations of the Mfongo system around Mt. Kilimanjaro. Water Utility Journal 22: 53-64, 2019.

Other publications

1. Kimaro, Jerome. "A Review on Managing Agroecosystems for Improved Water Use Efficiency in the Face of Changing Climate in Tanzania". Advances in Meteorology 2019 (2019).
2. Kimaro, Jerome, and Luther Lulandala. "Forest Cover and Land Use Change in Ngumburuni Forest Reserve, Rufiji District, Tanzania". Journal of Environment and Ecology 4, no. 2 (2013): 113.
3. Kimaro, J., and L. Lulandala. "Contribution of non-timber forest products to poverty alleviation and forest conservation in Rufiji District—Tanzania". Livestock Research for Rural Development 25, no. 5 (2013).
4. Kimaro, J., and L. Lulandala. "Human influences on tree diversity and composition of a coastal forest ecosystem: the case of Ngumburuni forest reserve, Rufiji, Tanzania".International Journal of Forestry Research 2013 (2013).
5. Kimaro, J., S. Liseki, W. Mareale, and C. Mrisha. "Enhancing rural food security through improved beekeeping in Northern Tanzania".Livestock Research for Rural Development 25, no. 12 (2013).

6. Kimaro E G, Mlangwa J E D, Lyimo-Macha J and Kimaro J G (2013): The influence of women groups on income obtained from small-scale dairy cattle production: A case of Arumeru district, Tanzania. Livestock Research for Rural Development. Vol. 25(4) 2013.

List of conference contributions

1. J. Kimaro and L. Lulandala (2009). Changes in Vegetation Cover and Tree Biodiversity in Ngumburuni Forest Reserve, Rufiji District, Tanzania. 7th TAWIRI Scientific Conference, 2nd – 4th December 2009, Corridor Springs, Arusha (Talk).

2. J. Kimaro, B. Huwe and C. Bogner (2015). Soil erosion under different vegetation cover in cultivated areas of Mt. Kilimanjaro. 9th TAWIRI Scientific Conference, 4th – 6th December 2016, Corridor Springs Hotel, Arusha, Tanzania (Poster).

3. J. Kimaro, Valeska Scharsich, B. Huwe and C. Bogner. Social perspectives of agricultural water in the cultivated areas of Mt. Kilimanjaro. EGU General assembly 2017, 23rd – 28th, Vienna, Austria (poster).

4. J. Kimaro, Valeska Scharsich, B. Huwe and C. Bogner. Management of traditional irrigation canals in the southern slopes of Mt. Kilimanjaro. BayCEER 8th Workshop – 13th October 2018. NW III, Bayreuth University, Germany (poster).

Book chapter

1. J. Kimaro, Valeska Scharsich, B. Huwe and C. Bogner, Distribution and discharge of irrigation canals around Mt Kilimanjaro in : Hemp, C., Böhning-Gaese, K., Fischer, M., & Hemp, A. (2018). The KiLi Project: Kilimanjaro ecosystems under global change: Linking biodiversity, biotic interactions and biogeochemical ecosystem processes. Senckenberg Gesellschaft für Naturforschung.

(Eidesstattliche) Versicherungen und Erklärungen

(§ 8 Satz 2 Nr. 3 PromO Fakultät) Hiermit versichere ich eidesstattlich, dass ich die Arbeit selbstständig verfasst und keine anderen als die von mir angegebenen Quellen und Hilfsmittel benutzt habe (vgl. Art. 64 Abs. 1 Satz 6 BayHSchG). (§ 8 Satz 2 Nr. 3 PromO Fakultät) Hiermit erkläre ich, dass ich die Dissertation nicht bereits zur Erlangung eines akademischen Grades eingereicht habe und dass ich nicht bereits diese oder eine gleichartige Doktorprüfung endgültig nicht bestanden habe. (§ 8 Satz 2 Nr. 4 Promo Fakultät) Hiermit erkläre ich, dass ich Hilfe von gewerblichen Promotionsberatern bzw. –vermittlern oder ähnlichen Dienstleistern weder bisher in Anspruch genommen habe noch künftig in Anspruch nehmen werde. (§ 8 Satz 2 Nr. 7 PromO Fakultät) Hiermit erkläre ich mein Einverständnis, dass die elektronische Fassung der Dissertation unter Wahrung meiner Urheberrechte und des Datenschutzes einer gesonderten Überprüfung unterzogen werden kann. (§ 8 Satz 2 Nr. 8 PromO Fakultät) Hiermit erkläre ich mein Einverständnis, dass bei Verdacht wissenschaftlichen Fehlverhaltens Ermittlungen durch universitätsinterne Organe der wissenschaftlichen Selbstkontrolle stattfinden können.

....

Ort, Datum, Unterschrift

Appendix 1: Socio-economic data on soil erosion study

The questions and answers of chapter 4 have been included in the DVD.