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ANALYSIS OF SOIL QUALITY, FARMERS' KNOWLEDGE AND MANAGEMENT PRACTICES IN MOUNT KENYA EAST REGION

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DEDICATION

This work is dedicated to:

The memory of my beloved mum, Elizabeth Nekesa, who passed on 17 years ago when I was just enrolling for my undergraduate studies. I had promised to make my mother the happiest woman through achievement of monumental academic success, and I hope that I have partly fulfilled the promise. How I wish she was alive today to enjoy the fruits of her sacrifice and prayers and to share the joy of celebration on my graduation with a Doctor of Philosophy degree.

My dad, Eliud Wawire Nambami, you not only worked so hard to provide for the family, but also incalcated in us principles of hardwork and encouraged me to believe in myself.

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TABLE OF CONTENTS

DECLARATION ii

DEDICATION iii

ACKNOWLEDGEMENTS iv

TABLE OF CONTENTS vi

LIST OF TABLES ix

LIST OF FIGURES xii

LIST OF EQUATIONS xiv

LIST OF ABBREVIATIONS AND ACRONYMS xv

1. INTRODUCTION 1

1.1 Background 1

1.2 Problem Statement and Justification 2

1.3 Research Objectives 3

1.4 Research Questions 3

2 LITERATURE REVIEW 5

2.1 Introduction 5

2.2 Soil Resources of Kenya 5

2.2.1 Distribution of major soil resources 5

2.2.2 Soil information, soil property data and maps 9

2.2.3 Declining Soil Fertility 11

2.3 Indigenous Soil Classification and Soil Assessment 12

2.3.1 Introduction 12

2.3.2 Indicators of soil fertility among smallholder farmers 13

2.4 Comparison of Local Soil Knowledge and Scientific Assessment of Soil Quality .. 17

2.5 Farm Management Practices and the Influence on Soil Fertility 23

2.5.1 Overview 23

2.5.2 Organic and inorganic fertilizer 23

2.5.3 Agroforestry 24
2.5.4 Fallowing 24
2.5.5 Organic resource management practices (conservation tillage) 25
3 MATERIALS AND METHODS 26
3.1 Description of the Study Area 26
3.2 Sampling Design 30
3.2.1 Soil sampling design 30
3.2.2 Designing of Farm Household survey and interviews 35
3.3 Field Work and Data Collection 36
3.3.1 Soil sampling 36
3.3.2 Questionnaire survey and interviews 38
3.3.3 Laboratory measurements 39
3.3.4 Mid Infrared (MIR) Spectra of soil samples 40
3.4 Methods of Data Analysis 42
3.4.1 Characterization and classification of soils of the study area 42
3.4.2 Farming systems, soil fertility management practices (SFMP), and determinants of SFMP adoption 44
3.4.3 Local indicators of soil fertility, and comparison of farmers' and scientific soil fertility measurements. 46
3.4.4 The influence of farmers' socio-economic and management practices on soil quality. 49
4 RESULTS AND DISCUSSION 53
4.1 Results 53
4.1.1 Soil Characterization of Sampled Farms 53
4.1.2 Farming Systems and Soil Fertility Management Strategies 65
4.1.3 Comparing Farmers' Soil Fertility Assessment and Scientific Measurements . 78
4.1.4 Influence of Farm Management Practices on Soil Fertility. 83
4.2 Discussion 100

4.2.1 Soil characterization and classification 100
4.2.2 Soil fertility Management practices 106
4.2.3 Farmers' and scientific soil fertility assessments compared 116
4.2.4 Relationship between Farm management practices, socio-economic and soil quality 119
5 CONCLUSION AND RECOMMENDATIONS 123
5.1 Conclusion 123
5.2 Recommendations 127
6 KEY SCIENTIFIC FINDINGS AND IMPORTANT OUTPUT 129
SUMMARY 131
REFERENCES 134
APPENDICES 164

LIST OF TABLES

Table 3.1. Selected soil variables for PCA and MCA analysis 43
Table 3.2. Variable selection for cluster analysis for soil fertility management practices 44
Table 3.3. Description of independent and dependent variables used in Fisher's and Welch's model...45
Table 3.4. Indicator scoring for calculation of the additive soil quality index 48
Table 3.5. Socio-economic and farm variables used in CATPCA model 49
Table 3.6. Soil properties variable used in Factor analysis...50
Table 4.1. R^2 and RMSE results of soil properties predictions 53
Table 4.2. Overall descriptive statistics of laboratory measurements of soil properties and across the three depths 54
Table 4.3. Results of ANOVA showing tendencies of soil properties across the three sampling depths (0-20, 20-50, 50-100cm)...56
Table 4.4. Principal qualifiers associated with soils of Mount Kenya East region 59
Table 4.5. Supplementary qualifiers used in the classification of soils in Meru and Tharaka Nithi 60
Table 4.6. Frequencies of Diagnostic horizons and properties associated with RSGs of Mount Kenya East region 60
Table 4.7. Major socio-demographic characteristics of farms in Mount Kenya East.............65
Table 4.8. Major cropping systems practiced in Meru and Tharaka Nithi 66
Table 4.9. Types and numbers of livestock kept by farmers in the study area 67
Table 4.10. The use of Fertilizer and manure in combination, among farmers in the study area 68
Table 4.11. Sources and types of manure used by farmers in Mount Kenya East region 71
Table 4.12. Correlations among the various SFMP based on farm household's usage patterns 73
Table 4.13A. Fisher's Exact test of significance of explanatory variables 74
Table 4.14. Welch t test of significance of determinants of soil fertility management practices (continuous variables)..76
Table 4.15. Fisher's Exact test of significance of determinants of inorganic fertilizer and manure use 77
Table 4.16. Welch's t-test of significance of determinants of inorganic fertilizer and manure use 77

Table 4.17. Descriptive soil quality indicators among farmers for high and low fertility fields 78
Table 4.18.Varimax-rotated factor analysis for descriptive soil quality scores.......................80
Table 4.19. Independent Samples t-test results of mean soil fertility measures for topsoils in high and low fertility soils 80
Table 4.20. Additive SQI for selected soil fertility indices for topsoils (0-20 cm) 81
Table 4.21. Varimax-rotated factor analysis for the FA-SQI derivation 82
Table 4.22.P-values based on ANOVA to determine the relationship between management practices and soil properties...84
Table 4.23. Principal component loadings of household socio-economic variables based on CATPCA analysis using variable principal normalization 88
Table 4.24. Principal component loadings of field characteristics based on CATPCA analysis using variable principal normalization...90
Table 4.25. Principal component loadings of soil variables based on CATPCA analysis using variable principal normalization 92
Table 4.26. Characterization of identified farm types based on p-value of one-way analysis of variance (equality of mean) of soil properties. 95
Table 4.27. Frequency distribution of farm management characteristics across clusters (farm types) in Upper Eastern Kenya. 96
Table 4.28. Characterization of identified farm types based on p-value of one-way analysis of variance (equality of mean) of socio-economic characteristics...98
Table 4.29. Comparison of households' socioeconomic characteristics across the identified farm types in upper Eastern Kenya 99

Table A 1. Fisher's Exact test of Relationship among selected explanatory variables..........185
Table A 2. Correlation between Household Farm size and access to Government subsidized fertilizer using ANOVA...185
Table A 3. Correlation between Farmer's income and access to Government subsidized fertilizer using ANOVA...185
Table A 4. Descriptive statistics of manure application and soil properties.........................187
Table A 5. Descriptive statistics of Fallowing and soil properties 188
Table A 6. Descriptive statistics of Agroforestry and soil properties....................................189
Table A 7. Descriptive statistics of Minimum tillage and soil properties 189
Table A 8. Descriptive statistics of Mulching and soil properties..191

Table A 9. Descriptive statistics of Crop residue application and soil properties 191
Table A 10. Descriptive statistics of farming type and soil properties 192
Table A 11. Descriptive statistics of land use and soil properties 194
Table A 12. Soil pH Threshold values 196
Table A 13. SOC Threshold values 197
Table A 14. Results of soil properties, soil classification and the generated Reference soil groups 198
Table A 15. Correlations of soil properties 205

LIST OF FIGURES

Figure 2.1. Distribution of major reference soil groups in Africa: soil atlas of Africa (Jones, et al., 2013) 6
Figure 2.2. Distribution of major reference soil groups of Kenya (Sombroek et al., 1982) 8
Figure 2.3. The Wandering Jew (Commelina bengalensis L.), a high fertility indicator weed species. Photo credit:Author, 2019. 15
Figure 3.1. Map of Kenya (a) showing the Location of Meru and Tharaka Nithi Counties (b), and the distribution of sampling points within the study area (c) 26
Figure 3.2. Major Reference Soil Groups of the study sites (Source: Dijkshoorn et al., 2011) 29
Figure 3.3. Topographical Wet Index of the study area 33
Figure 3.4. Elevation (A) and Slope (B) of the study area 34
Figure 3.5. Map of the study area showing selected sites for soil sampling and social data survey 36
Figure 3.6. Soil sampling: a cleaned open soil profile (A), collection of soil samples through augering (B); obtaining of samples from an open profile (B). 37
Figure 3.7 Administering farm household questionnaire to a farmer. Photo taken during the survey for this study in January 2019. 38
Figure 3.8. FTIR Infrared spectrum in the MIR region of a soil sample 41
Figure 4.1. Soil property maps for selectected attributes: soil organic carbon (A), pH (B), Base saturation (C) and Cation exchange capacity (D) 55
Figure 4.2. Soil property maps for selectected attributes: Clay (A), Available P (B) and extractable K 56
Figure 4.3. Frequencies of dentified Reference Soil Groups in the visited sites 58
Figure 4.4. Distribution of Reference soil groups in the study sites 59
Figure 4.5. Tendencies of CEC, pH, SOC, BS, and texture proportions across the RSGs 62
Figure 4.6. Tendencies of Exchangeable bases and mineral nutrients across the RSGs 63
Figure 4.7. PCA biplot of soil properties 64
Figure 4.8. Different soil fertility management strategies practiced by farmers in the study area 67
Figure 4.9. Crop residue management approaches used by farmers in Meru and Tharaka Nithi 68
Figure 4.10. Fertilizer use patterns during planting and top dressing 69

Figure 4.11. Farmer's fertilizer application patterns 70
Figure 4.12. Manure application in Meru and Tharaka Nithi based on farm location 70
Figure 4.13. Sources of manure (A) and fertilizers (B) and and their proportional contribution to the total amount of fertilizer used on the farm. Values are in percentages..........................71
Figure 4.14. Proportion of households and the different kinds of fertilizers used...................72
Figure 4.15. Dendrograms showing common combinations of ISFM technologies among farming households...74
Figure 4.16. Mean soil quality ratings for high and low and fertility plots in Mount Kenya East region 79
Figure 4.17. Relationship between quantitative and qualitative soil quality indices in the study area (0-20 cm depth). Farmer-descriptive SQI is correlated against additive SQI (A) and Factor analysis-generated SQI (B)...83
Figure 4.18. Association between Soil nutrients and DAP application rates 87
Figure 4.19. Correlation biplot showing the relationship between socioeconomic variables. 89
Figure 4.20. Correlation biplot showing the relationship between farm variables..................91
Figure 4.21. Plots of component loadings obtained from factor analysis describing the relationships among soil properties 93
Figure 4.22. Farm household's membership across the clusters 94
Figure 4.23. Distribution of cluster membership in the study area...95

Figure A 1. Income differentiation across farm households..208

LIST OF EQUATIONS

(1)..31
(2)..32
(3)..32
(4)..33
(5)..34
(6)..35
(7)..48

LIST OF ABBREVIATIONS AND ACRONYMS

AfSIS	Africa Soil Information Service
AGRA	Alliance for a Green Revolution in Africa
AHC	Agglomerative Hierarchical Clustering
ASHC	Africa Soil Health Consortium
ATGS	Agriculture Sector Transformation and Growth Strategy
CA	Cluster Analysis
CATPCA	Categorical Principal Analysis
CEC	cation exchange capacity
ESMK	Exploratory Soil Map of Kenya
FET	Fisher's Exact Test
FT	Farm type
GDP	Gross Domestic Product
HC	Hierarchical clustering
KENSOTER	Kenya Soil and Terrain
KSS	Kenya Soil Survey
MOA	Ministry of Agriculture
NCPB	National Cereals and Produce Board
OFRA	Optimizing Fertilizer Recommendations in Africa
PCA	Principal Component analysis
RSGs	Reference soil groups (RSGs)
SDGs	Sustainable development goals
SFMP	Soil fertility management practices
SOC	Soil organic carbon

SOM	Soil organic matter
SOTER	Soil and Terrain digital database
SOTER_UT	Soil and Terrain digital database for Upper Tana
SSA	Sub-saharan Africa
SWAT	Soil and Water Assessment Tool
WoSI	World Soil Information

1. INTRODUCTION

This chapter begins by providing a general picture of the problem under investigation. The research problem, theoretical arguments and the importance of the study are described. Further, this section is organized under the following sub-headings: the background, problem statement, research objectives and research questions. The background provides a general description on the current status of soil quality, soil information and the management efforts. The problem statement highlights the gaps that necessitate further intervention. Research objectives succinctly state the actual purpose of this research. Research questions provide key questions presented by the research to achieve the stated objectives.

1.1 Background

Soil is arguably the foundation of agriculture. It is the most valuable and widespread natural resource and the economic engine to the agricultural-based livelihoods. On the flipside however, there has been consistent decline in land productivity stemming from declining soil fertility (NAAIAP, 2014).

Soils can be considered as life enabler courtesy of the ecosystems services that they deliver on Earth. According to the Food and Agriculture Organization (FAO, 2015b), soils provide the following ecosystem functions and services: i) provision of food, ii) fibre and fuel; iii) nutrient cycling; iv) water purification, soil contaminant reduction and fresh water storage; v) carbon sequestration; vi) foundation for human infrastructure; vii) flood regulation; viii) habitat for organisms; ix) provision of construction materials; x) cultural heritage and xi) climate regulation. For soil to deliver on most of these functions, it must be maintained in good health.

The criticality of these ecosystem functions and services places soil (and of course agriculture) at the heart of sustainable development goals (SDGs) (Bouma & Montanarella, 2016; Tóth et al., 2018). The increase in global population and the resulting pressure on the natural resources (including water, land and nutrients), clearly puts soil on spot, calling for sustainable management of the resource to ensure supply of adequate food and achievement of SDG2 (zero hunger). Similarly, environmental issues including land degradation, soil erosion, and decline in soil organic carbon (SOC) are strongly connected with decline in environmental quality, thus putting the livelihoods of a significant global population at risk (Bouma et al., 2017). Other goals directly linked with soil include SDG1 (no poverty), SDG3 (good health and well-being), SDG 6 (clean water and sanitation), SDG 13 (climate action) and SDG 15 (life on land). Soil is also indirectly critical in achieving the rest of the SDGs (EC, 2006).

The demonstrated uniqueness of soil in influencing the availability and utilization of other natural resources (including water, land, nutrients and biodiversity) is more than sufficient justification for the increasing interest among the scientific community in finding ways to sustainably manage this resource, and stem the runaway soil fertility decline, which has been a trademark for soils in sub-Saharan Africa (SSA) (Andriesse & Giller, 2015; Bekunda et al., 2005).

The degradation of soil and deteriorating soil fertility is considered a serious threat for human existence and the natural environment due to changing climate, topography, soil characteristics, and uniqueness of agriculture (Tully et al., 2015). The devastating impacts of agricultural practices on soil quality include salinization, erosion, compaction, desertification, and pollution (Andriesse & Giller, 2015). In order to design appropriate sustainable strategies for addressing these effects, research should be geared towards developing an accurate soil quality monitoring system at multiple scales based on a functional evaluation of soils.

Understanding of the problems affecting soil resources is a critical prerequisite in addressing these challenges and ensuring that soil effectively delivers its functions. In response to this reality, there is increasing interest at national, regional and international levels on the strategies to enhance and sustain healthy soils.

1.2 Problem Statement and Justification

There is increasing demand for accurate, consistent and comprehensive soil data at small-scale level. Informed farming decisions depend heavily on quality, reliable and up-to-date soil information. In response, soil resource inventories have been undergoing dramatic revolution from the use of traditional soil surveys to sophisticated digital techniques. Consequently, the quantity and quality of digital soil data sets at global, regional, national and local scales has increased tremendously (Dobos et al., 2001). However, access to soil information remains a major challenge. Many parts of the world including Kenya, lack or little survey information, or only scanty generalized small-scale soil maps and data are available. Similarly, there is lack of harmonized databases occasioned by unsystematized sampling design, rendering comparison of different surveys difficult, thus compromising the accuracy of soil data. Most of these databases are based on either regional or national scale (Dobos et al., 2001), thus highly generalized and unsuitable for decision-making at farm level (which are characterized by high variability of soil properties at very short distances). Most of the existing soil databases are outdated with little efforts being made to update the resources, largely due to high costs of survey and laboratory analyses (Mutuma, 2017). Fortunately, at the continental level, the Africa Soil Information Service (AfSIS) has actively been working on bridging this major gap in soil spatial information. The database generated by AfSIS has been the major input to digital soil mapping activities (AfSIS, 2013). Information on distribution and the nature of soil resources is critical in making decisions on efficient land use and management and to help deal with food security, global climate change and other looming environmental and economic issues.

1.3 Research Objectives

The purpose of this study is to evaluate the quality of soil Mount Kenya East region and determine management-induced changes in soil properties. To achieve this aim, the following objectives were defined.

1. To characterize and classify soils of the visited sites
2. To describe the farming systems and soil management practices and explore the socio-economic determinants of soil fertility management strategies.
3. To determine local indicators of soil fertility and compare scientific assessment and farmers' soil fertility perception.
4. To evaluate the influence of farmers' socio-economic characteristics and management practices on soil quality.

1.4 Research Questions

To achieve the stated objectives, the following research questions were formulated.

1. **Objective one**

i. What are the defining characteristics of the soils of Mount Kenya East region?
ii. How do these properties vary with the sampling depth intervals?
iii. What are the major reference soil groups (RSGs) of Mount Kenya East region?
iv. How do soil attributes vary across the identified RSGs?

2. **Objective two**

i. What are the socio-economic and demographic characteristics of farm households in Mount Kenya East region?
ii. What are the characteristics of farming systems in the study area?
iii. What are the soil fertility management practices (SFMP) used by farmers in the study region?
iv. What are the combination clusters of SFMP as used by farmers?
v. How do farm household socio-economic and demographic characteristics correlate with adoption of SFMP?

3. Objective three

i. What are the local indicators of fertile and infertile soils used by farmers?
ii. How important are the indicators in predicting soil fertility?
iii. How does farmers' soil fertility evaluation correlate to scientific measurements of soil attributes?

4. Objective four

i. How do management practices relate with soil characteristics?
ii. How can farm households be grouped (typologies) based on socio-economic, farm management practices and soil variability?
iii. How do soil characteristics vary across the identified farm household groups (typologies)?

2 LITERATURE REVIEW

2.1 Introduction

This section reviews and presents a critical assessment of existing literature related to the subject of investigation, with the aim of identifying the gap in knowledge, and thus the justification for this study. The chapter is organized under several themes related to each of the stated objectives.

Overview of the soil resources provides a background of soil, highlighting the state of soil as a capital resource at regional, national and local levels. The developments made in promoting soil information, through development of soil databases, are highlighted. The place of soil within the Sustainable Development Goals (SDGs), a global development framework, is presented. Characteristics of the major soils in Kenya are discussed. Setbacks in the effort ensure a healthy, productive, and sustainable soil, are discussed.

Literature on farmers soil fertility perceptions highlight the different indicators used by farmers across various regions in assessing soil fertility. Further, a comparison of farmers' soil knowledge and scientific measurements, is discussed. Literature on soil fertility management practices among smallholder farmers, is reviewed. The interaction between farmers' knowledge, management practices and soil fertility are discussed. Some selected methods of data analysis are described.

2.2 Soil Resources of Kenya

2.2.1 Distribution of major soil resources

Sub-Saharan Africa is characterized by a wide range of soil types (Figure 2.1), including Arenosols (21.5%), Leptosols (17.5%), Cambisols (10.8%), and Ferrasols (10.3%). The diversity of these soils is attributed to the distribution of soil forming factors (Jones et al., 2013). The reference soil groups face varying types and degrees of soil constraints (Tully et al., 2015).

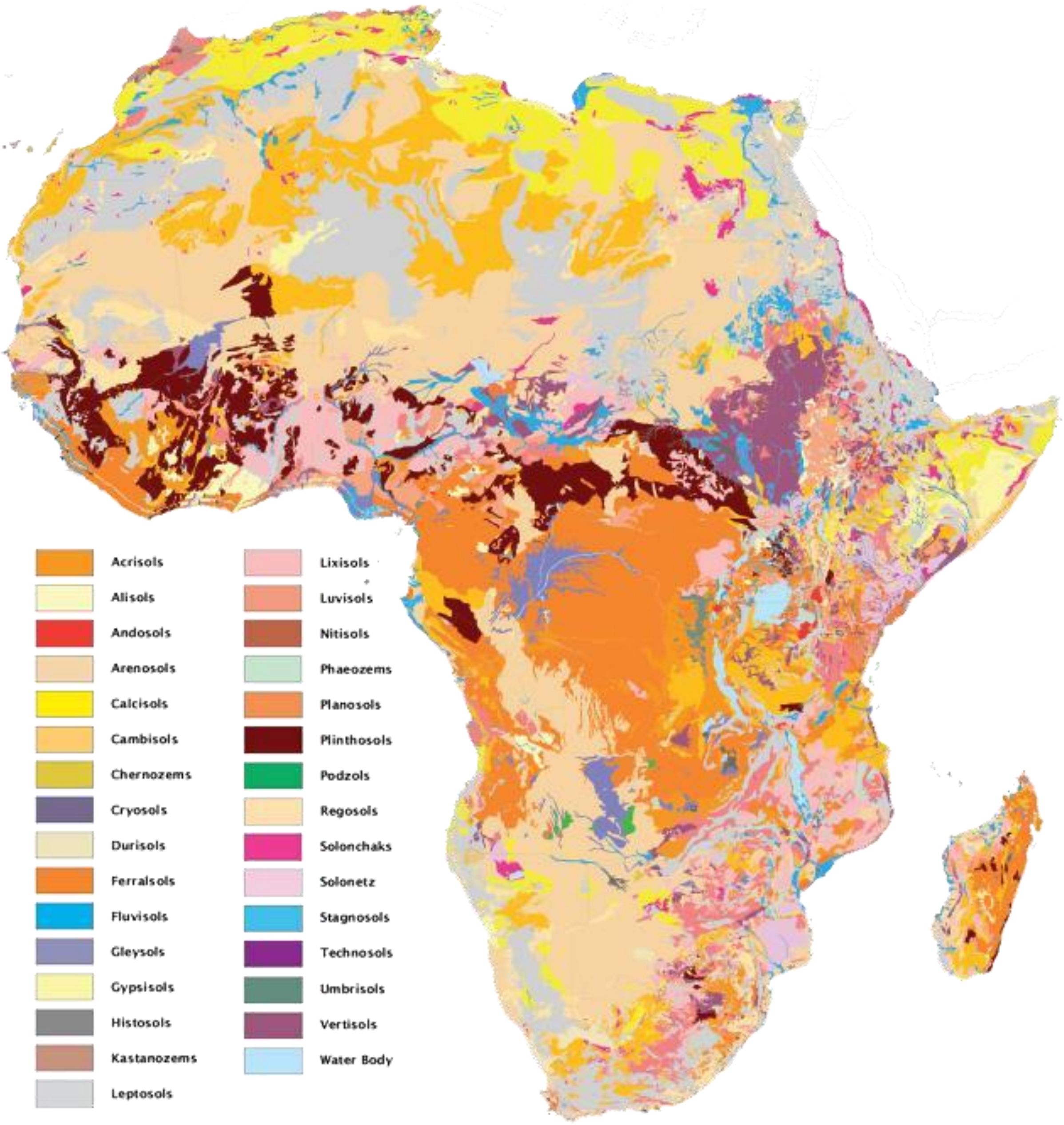

Figure 2.1. Distribution of major reference soil groups in Africa: soil atlas of Africa (Jones, et al., 2013)

Kenya has more than 25 major soil groups (Figure 2.2) with diverse characteristics. The major soils used in agriculture include Nitisols, Ferrasols, Acrisols, Vertisols, Lixisols and Luvisols. The soil description was performed according to Sombroek et al. (1982), while soil classification was done based on FAO 2006 (NAAIAP, 2014). The wide range of soils is a product of high variability in soil attributes resulting from the interaction among the soil forming factors, namely climate, topography, parent material, organisms and time (Jones et al., 2013; NAAIAP, 2014). The influence of altitude dominates the climate of the highlands including the survey area. Based on altitude and climatic characteristics, the highlands can be classified into four major climatic zones including the Alfo-alpine zone (above 3,050 m), the

Upper Highland zone (2,450 to 3,050), the Lower Highland zone (1,850 to 2,450) and the Upper Midlands zone (1,500 to 1,850). Some soils are associated with uplands (e.g. Nitisols commonly found in the Upper Midland zones) while others commonly occur in lowlands (e.g. Acrisols). Geologically, Kenya has diverse rocks, including Basement System rocks of pre-cambrian age, Tertiary volcanics and Cenozonic unconsolidated sediments. The geology of the survey area is mainly volcanic rock, ash and old metamorphic rocks (Muchena & Gachene, 1988a). The variation in parent material (geology), relief and climate gives rise to a wide range of soils. These soil resources range from sandy to clayey, shallow to very deep and low high fertility. A significant proportion of theses soils are characterized by serious challenges including salinity/sodicity, acidicity, fertility and drainage issues (Infonet, 2019). Further natural causes such as low cation exchange capacity (CEC), low soil organic matter (SOM) and impacts of climate change result in low productivity of these soils (Shepherd & Walsh, 2007).

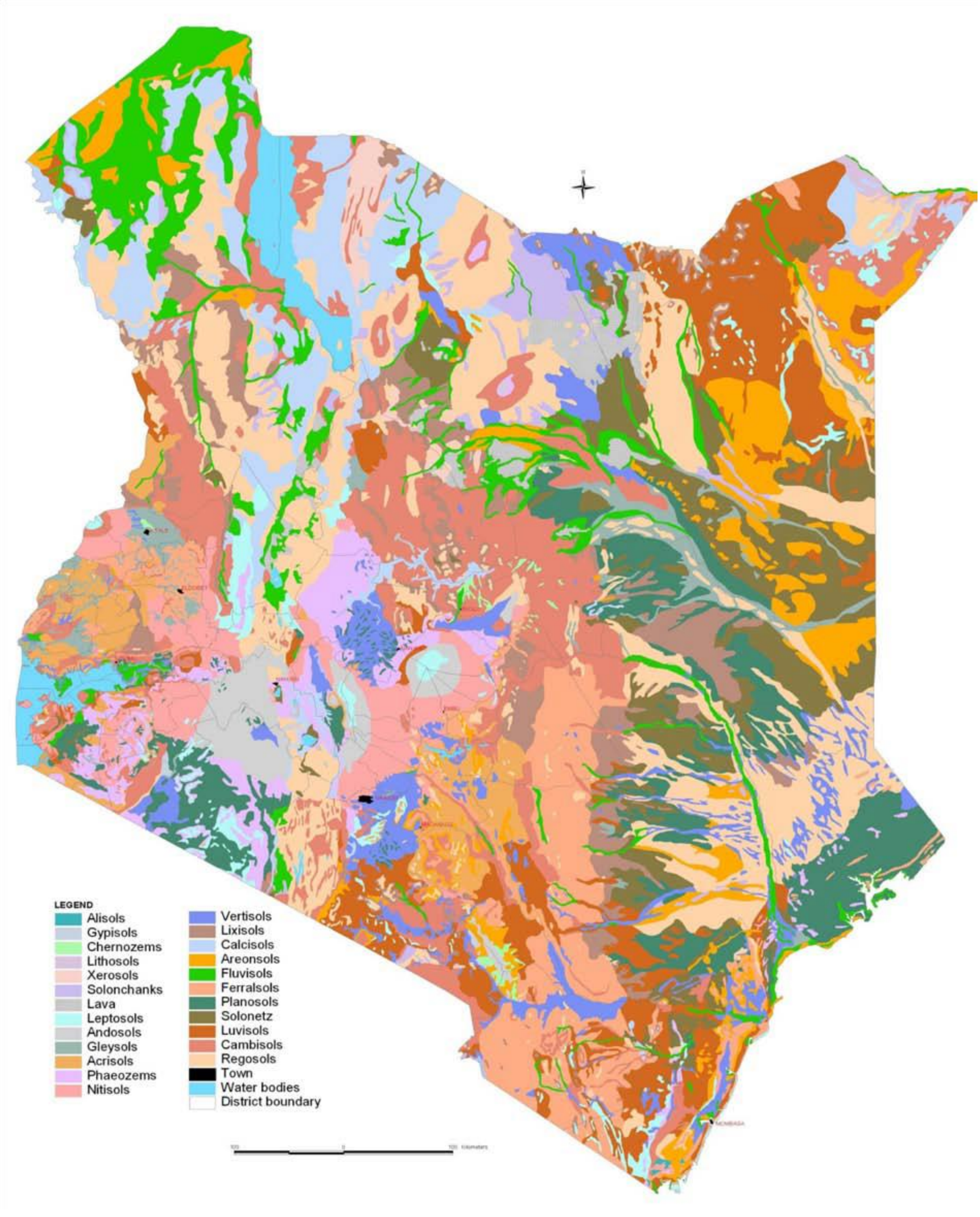

Figure 2.2. Distribution of major reference soil groups of Kenya (Sombroek et al., 1982)

The predominant soils in the study area (situated in Mount Kenya East region) include Nitisols and Acrisols, occuring mostly to the northern (upper areas) and southern (lower) parts of the survey area, respectively. Nitisols are derived from basic volcanic rocks and are found extensively in Central Kenya, including both slopes of Mount Kenya (HIROSE, 1987).. They are characterized by deep friable clays, and are one of the most productive soils of the humid tropics. Due to their deep (often greater than 200 cm) and porous solum and the stable soil structure, Nitisols are more resistant to erosion (Jaetzold & Schmidt, 1983; NAAIAP, 2014). They are intensly used for cultivation of plantation crops (tea and coffee) and food crops including banana(Gicheru & Kiome, 2000). Because of their structural stability, Nitisols can be cultivated even on moderately steep gradients. Their chemical properties vary greatly. Nitisols' organic matter content, base saturation and cation exchange capacity range from low to high (Muchena & Gachene, 1988a). Acrisols occur in the sub-humid areas, on the undulating to hilly topography, and are poor in organic matter content with low reserves of N, P and mironutrients (SOCO (Soybeans & Climbing Beans Project), 2017). Fortunately, these soils respond positively to ferilizers and application of soil organic matter (Infonet, 2019). They are strongly weathered with less than 50% base saturation. Acrisols are characterized by sealing and crusting, restricting rooting spreading, and are relatively low in water storage capacity compared to Nitisols.

Other common soils include Andosols, Umbrisols, Cambisols, Leptosols, Plinthisols and Gleysols.

2.2.2 Soil information, soil property data and maps

Accurate information on soil beyond regional and national scale is crucial, to support improved soil management and agricultural practices according to land potential (Odeh & McBratney, 2000). At farm level, soil information is a fundamental prerequisite for land and soil management decisions including fertilizer recommendations (Bindraban et al., 2018; Hartemink, 2008) Spatial evaluation of soil properties provides researchers with a clear understanding of the complex and dynamic ecosystems (Hively et al., 2011). Knowledge of soil properties and their influence on agriculture helps to inform implementation of sustainable agricultural and environmental management practices (Viscarra-Rossel, 2008). Even more important is the need to understand the impact of agricultural management and practices on the soil resources.

Agriculture is the bedrock of most of the sub-Saharan economies. In Kenya, agriculture contributes more than 33% of the county's Gross Domestic Product (GDP) (ATGS, 2019). There is overwhelming consensus among stakeholders on the importance of investing in sustainable and productive agriculture (FAO, 2015a). In the effort to combat the soil degradation trend in sub-Saharan Africa, several initiatives have been launched across the region including the Soil Health Program by Alliance for a Green Revolution in Africa

(AGRA) (AGRA, 2013), Optimizing Fertilizer Recommendations in Africa (OFRA) (CABI, 2017), Africa Soil Health Consortium (ASHC) (ASHC, 2020), PROIntensAfrica (CORDIS, 2015), Global Soil Partnership on Nutrient Management (FAO, 2015a). These programs have focused on a range of campaigns, including increased use of fertilizers, organic inputs and dissemination of Integrated soil fertility management (ISFM) technologies (Vanlauwe, Bationo, Chianu, et al., 2010). . However, because of limited investment in soil fertility campaign programs, researchers have projected an escalation in soil fertility decline (AfSIS, 2013; Shepherd & Walsh, 2007).

Developments in soil classification and documentation and updating of soil databases have widely been discussed (Grandjean et al., 2010; Hartemink & McBratney, 2008; Mutuma, 2017; Van Egmond et al., 2009; van Engelen & Dijkshoorn, 2013). The focus of new techniques and methodologies is on the provision of updated high-resolution soil information. Examples of these projects include iSoil (Van Egmond et al., 2009), e-SOTER (van Engelen, 2008)Digisoil (Grandjean et al., 2010), World soil information service or WoSIS (Batjes, 2009) GlobalSoilMap.net (Sanchez et al., 2009). Despite these efforts, the application of the information generated from the databases at farm management level remains a challenge due to the low level of scale used, unstandardized data collection and analyses methodologies (Dobos et al., 2001).

At the continental level, the Soil Atlas of Africa (Jones et al., 2013), is one of the most important sources of soil information in the region. Data for the database was drawn from various databases including the Harmonized World Soil Database (HWSD), FAO/UNESCO (FAO/UNESCO, 2003). Digital Soil Map, the soil and Terrain database (SOTER), WISE databases (Batjes, 2008; FAO/ISRIC, 2003).

Latest efforts to ensure reliable and accurate soil property data have been advanced by the International Soil Reference and Information Center (ISRIC) through the development of a collection of gridded soil property maps at a relatively high spatial resolution of 250 metres and which includes six depth intervals (Hengl et al., 2017).

In Kenya, the Exploratory Soil Map (ESMK) which was developed by the Kenya Soil Survey (KSS) at a scale of 1:1M (MOA, 1980), is the country's major source of soil information. The ESMK has undergone significant transformations over time, with the first provisional map (1:2 M scale) dating back to 1935 (Milne, 1935). Three editions of the second map (1:3 M) were produced between 1959 and 1970. The ESMK's data was instrumental in the development of the world soil map (FAO/UNESCO, 1974).

Other important and recent sources of soil information include Kenya Soil and Terrain (KENSOTER) database (Kempen, 2007) and the Africa Soil Information Service (AfSIS) library (AfSIS, 2013). KENSOTER database at scale 1:1 M. is a creation of KSS and ISRIC, is based on SOTER methodology. The current version (2.0) which is an improvement of the earlier version, includes additional and new profile data, substituting the synthetic profile data (Kempen, 2007).

The data for Mount. Kenya region and the surroundings is housed by Soil and Terrain (SOTER) database for the Upper Tana River catchment (SOTER_UT) at 1:250,000 and SOTER_UT at 1:100,000. The SOTER_UT database, which is based on reconnaissance soil surveys,was compiled by KSS and ISRIC-World Soil Information (in the framework of Green Water Credits Project) with the primary purpose of assessing the hydrology of the basin using the model Soil and Water Assessment Tool (SWAT) to determine the impact of land management practices change in the basin's water balance (Dijkshoorn et al., 2011).

One of the shortcomings of the available soil information databases, is that most of them could be outdated. This is due to overreliance on the historic legacy soil data, and thus inheriting the same gaps in the measured analytical data held. Promisingly, however, ISRIC-WoSI has developed a methodology (taxotransfer rule-based procedures) for updating these databases by filling common identified gaps in mother SOTER databases to generate secondary (SOTWIS) datasets for general-purpose application (Batjes, 2010).

2.2.3 Declining Soil Fertility

One of the major threats to agricultural productivity in developing countries is declining soil fertility (Lal & Steward, 2010)**.** This has been attributed to several factors including soil degradation processes, desertification, continuous use of extractive farming practices, poor agronomic practices, low use of important agricultural inputs (Tittonell, 2014) and minimal efforts to restore soil degradation (Lal & Steward, 2010). Climatic change shocks and the resulting hydrological extreme events as well as competing demands for limited soil resources, have further complicated compounded the problem (Hooper, et al., 2005).

Deteriorating soil fertility is currently regarded as food security challenge in many developing countries (UNDESA, 2013). Low soil fertility is considered one of the major factors responsible for diminishing yields on small-scale farms particularly in low potential areas across Africa, and for Africa's depressed agricultural productivity compared to other regions (Corbeels et al., 2000; Onduru et al., 2001). In fact, African countries, Kenya included, are home to some of the world's most degraded soils, with more than 75 percent of African farm land classified as severely depleted due to poor soil management practices on the fragile soils. According to the International Centre for Soil fertility and Agricultural Development, Africa loses 8 million metric tons of soil nutrients annually, and more than 95 million hectares of land have been hugely degraded (Chukwuka & Omotayo, 2009; Henao & Baanante, 2001; Jama et al., 2013).

There is strong evidence worldwide supporting the link between poverty and soil conditions. Hartemink (2005) argues that "Poor soils make people poorer" and "poor people make soils worse." This clearly demonstrates that unless the issue of declining soil fertility is addressed, the poor smallholder farmer can only get poorer and the United Nations SDGs, and in particular SDG 1 (no poverty) and SDG2 (zero hunger) will remain untenable. Soil information is the first step towards ensuring quality soils by informing sustainable management and restoring of degraded soils. Sustainable management of soils is the key to quality healthy soils and thus quality life.

2.3 Indigenous Soil Classification and Soil Assessment

2.3.1 Introduction

Indigenous soil classification and characterization exist virtually the world over and is the heart of traditional farming systems in developing countries where a substantial proportion of farmers lack or have limited access to extension services including soil analysis (Handayani & Prawito, 2010; Murage et al., 2000). A number of studies have assessed farmers' knowledge about soils and local classification systems (e.g. Ali, 2003; Gray & Morant, 2003; Macharia & Ng'ang'a, 2005; Martin & Santos, 2016; Rist & Dahdouh-Guebas, 2006; Weib, 2006).. Farmers have deep understanding of soils and their resources (Martin & Santos, 2016; Weib, 2006) based on the inherent traditional knowledge. They have a well-organized knowledge system about the quality of their soils, nutrient provision, nutrient loss and nutrient cycling processes. While indigenous knowledge is based on experiences passed on from generation to generation, they also change, adapt as well as assimilate new ideas (Becker & Ghimire, 2003; Dawoe et al., 2012; Rist & Dahdouh-Guebas, 2006). The criteria used by farmers in selecting the best use for their soil resources and design management practices for their land is based on their experiences backed by their ability to observe soil attributes (Martin & Santos, 2016).

A study conducted by Dawoe et al. (2012) to assess local knowledge and perceptions of soil fertility among Ashanti farmers in Ghana, established various indicators used by farmers to determine soil fertility, including soil colour, crop yield, soil workability, water holding capacity, availability of fresh worm casts, availability of soil-micro-fauna, presence of indicator weeds, stoniness of soil, crop height and growth rate, and level of deficiency symptoms. In a study to evaluate productive soils by farmers in Kenya's Central highlands, the presence of earthworms and beetle larvae were regarded as indicators of fertile soil. Plant species such as *Commelina benghalensis* (L.) is linked to productive soil, while plants such as *Digitara scalarum* (Chiov.) and *Rhynchelytrum repens* (Willd.) C.E. Hubb, are associated with infertile soils (Murage et al., 2000).

This knowledge can be location-specific and may also vary across social differentiations, namely wealth, occupation, age, gender and ethnicity (Pawluk et al., 1992). Several studies on traditional subsistence farming systems in the tropics acknowledge existence of a stable farmers' understanding of their local ecosystems. These studies suggest a critical role of farmers' knowledge of soils and their management in developing more sustainable farming systems (Isaac & Dawoe, 2011; Rist & Dahdouh-Guebas, 2006).Indigenous farmers' knowledge of soils including local indicators of soil quality are a prerequisite in developing of technologies and management interventions. The hope for sustainable agriculture, however, is pegged on the capacity to integrate all experiences and not just reliance on one tradition at the exclusion of the other (Weib, 2006).

2.3.2 Indicators of soil fertility among smallholder farmers

Soil colour

Soil colour and texture is used by farmers as a major differentiating characteristic, which has been shown to tally formal soil classifications in ethnopedological studies (Talawar & Rhoades, 1998). In a study by Mairura et al. (2008), soil colour was used by over 60% of farmers to differentiate between fertile and infertile fields. Fertile fields (wet soil assessment) were darker in colour, while infertile sites showed light coloured soils, which was linked to high organic matter content (Desbiez et al., 2004; Fleskens & Jorritsma, 2010; Gobin et al., 2000).A study by Michel et al. (2015) in Cameroon showed that soil colour was evaluated visually by farmers, with black soil indicating fertile soils while fields with red soils were perceived to be less fertile.

Earthworms

The presence of earthworms has been recognized as an important soil biological indicator. Farmers were reported to utilize the presence of different types of earthworm species to differentiate soil fertility in Latin American soils(Lima & Brussaard, 2010). Due to the important role in soil ecosystems and their sensitivity to soil property changes, earthworms have been used for the assessment of contaminated soils (Römbke et al., 2007),, assessment of soil quality in different agroecosystems (Bartz et al., 2014) and to assess their behaviour to changes in soil properties (Paoletti et al., 1991). The roles of earthworms are recognized, including regulating soil physical structure, the decomposition of organic matter and enhancing nutrient availability to plants (Brown et al., 2000). Soil earthworm populations and their diversity can be an integral criterion in evaluating farming systems, thusbetter land management systems (Bartz et al., 2014).

Indicator weeds

In many parts of the world, small scale farmers have associated the condition of vegetation (both native and planted) with levels of field soil fertility (Dawoe et al., 2012; Desbiez et al., 2004; Murage et al., 2000). Some of the weeds indicating fertile soils in Kenya include comm *Commelina benghalensis* L. (Figure 2.3), *Galinsoga parviflora* L., *Bidens pilosa* L. and *Amaranthus* spp. Low fertility weed species include *Ageratum conyzoides* L., *Rhynchelytrum repens* (Wild) and *Tagetas minuta* L. (Murage et al., 2000).

This knowledge is ingrained in the minds of more observant farmers and thus needs to be further advanced through research. In Latin America, Suarez et al. (2001) reported agricultural weeds to indicate the level of agricultural disturbance on crop productivity. Natural and agricultural ecosystems respond socio-ecological processes through natural succession (Barrios et al., 2000).During these processes, the best adapted plants gradually replace those least adapted through a selection process that is exerted by climatic factors, nutrient deposition, and changes in soil characteristics. In farming systems such changes in agricultural weeds have been shown to be influenced by many factors, including differences in soil fertility (Suárez et al., 2001). Farmers observe changes in plant populations generated by changes in soil quality, which leads to the generation of farmer soil-crop knowledge systems (Barrios et al., 2000).

Figure 2.3. The Wandering Jew (Commelina bengalensis L.), a high fertility indicator weed species. Photo credit:Author, 2019.

Workability

Soil workability is a function of soil texture contribution by clay, sand, silt and organic matter contents. Farmers in Cameroon were reported to evaluate soil texture manually using the feel method by fingers, where three texture classes were distinguished (Michel et al., 2015). Soil texture further determines water holding capacity and potential level of nutrients (Weil & Brady, 2016). Fertile soil, based on farmers classification, has high water holding capacity (Adeyolanu & Ogunkunle, 2016; Corbeels et al., 2000).

Topography

Topography is regarded as a key indicator of soil fertility in relation to crop production (Barrera-Bassols & Zinck, 2003; Dawoe et al., 2012; Yeshaneh, 2015) and soil degradation potential (Yeshaneh, 2015). Farmers classified fields within valley bottom and middle lower slopes as fertile, while upper slopes were categorized as infertile (Corbeels et al., 2000; Dawoe et al., 2012; Yageta et al., 2019). Farmers are conscious of the fact that steep slopes are associated with increased rate of erosion resulting into soil fertility decline (Price, 2007). Topography affects soil fertility and crop yield in several ways including the redistribution (erosion and/or deposition) of soil particles, organic matter (OM), and soil nutrients (Pennock & De Jong, 1990). The upper slopes are largely sandy with low water holding capacity (Corbeels et al., 2000). Soil topography also influences water and nutrient availability, vertical and horizontal water redistribution in the soil (Verity & Anderson, 1990).

Water holding capacity

Water holding capacity (WHC) is the amount of water that a given soil can hold for crop use. WHC is influenced by the size of soil aggregates. Increased soil aggregation results in decreased available water (Bullock, 1992). Previous studies (e.g. Dawaoe et al., 2012; Yageta et al 2019) have demonstrated farmers' knowledge of WHC as an indicator of soil quality. Farmers expressed that a good soil is that with high water holding capacity. Soil texture and organic matter are the key components that determine WHC. By classifying soil as fertile based on texture and organic matter underlines farmers' understanding of the concept of WHC, which is important in managing irrigation.

Crop performance characteristics

Yield, Leaf colour

Several studies on local soil knowledge systems have shown crop yield to be a major indicator of soil quality used by farmers to classify and manage soils (Bioversity International et al., 2012; Corbeels et al., 2000). Crop yield in fertile fields has been shown to be different from infertile fields which are frequently stunted in growth. Crops from fertile fields were generally characterized with deep green and vigour vegetative parts, fast growth and high yields, due to differences in soil nutrients (Adeyolanu & Ogunkunle, 2016; Dawoe et al., 2012). Farmers in Tanzania reported that presence of green vegetation (leaves) especially during dry season was an indicator of a fertile field (Soil Water Management Research Group, 2003).

However, farmer descriptive knowledge is deficient in identifying yield-limiting nutrients and more detailed soil processes, implying that this should be complemented with scientific soil knowledge (Laekemariam et al., 2017).

2.4 Comparison of Local Soil Knowledge and Scientific Assessment of Soil Quality

The conventional scientific soil quality indicators include such parameters as bulk density, pH, water content, effective rooting depth, electrical conductivity, total C and soil temperature (Doran & Parkin, 1996). On the other hand, local indicators used by farmers are highly variable and include soil texture and structure, crop yield and vigour, soil colour, the presence and/or absence or abundance of certain local plants (weeds) and soil micro-fauna (Barrios, et al., 2006). Numerous case studies have revealed a strong correlation between farmers fertility indicators assessment and the analysed chemical characteristics (Corbeels et al., 2000; Murage et al., 2000). In the Philippines, Martin and Santos (2016) reported that apart from acidity and colour, all other six soil characteristics (texture, structure, consistency, drainage, depth and porosity) were assessed by farmers in the same way as those of the scientists.

Both farmers and scientists have significant knowledge of agriculture and traditions of experimentation but varied knowledge systems (Bentley, 1992) The two knowledge systems play a complementary role to each other. On one hand, scientific research provides a detailed understanding of soil biophysical processes while farmers offer the prerequisite context-specific knowledge necessary to customize this understanding based on existing biophysical and socio-economic conditions (Gray & Morant, 2003).

Indigenous knowledge and the local soil names used by farmers are greatly essential, though they pose some shortcomings, especially when one needs to apply the local names to a regional scale (Tabor et al., 1990). For instance, the presence of certain varieties of plants is a widely used indicator of quality soil (Dawoe et al., 2012; Desbiez et al., 2004; Martin & Santos, 2016). However, these plants vary across regions (Martin & Santos, 2016; Suárez et al., 2001). The plant indicator among Ikalahan farmers in Philippines is cogon or *Imperata cylindica* (Martin & Santos, 2016).. Indigenous soil classifications tend to miss out on the detailed and crucial detections that are not glaringly visible such as the actual pH level of the soils and the status of micro and macro elements available in the soil (Martin & Santos, 2016)..

Soil chemical analysis facilitates a clearer understanding of the kind and amount of inputs (such as fertilizer) to allocate for crop production on a given soil (Lapoot et al., 2010). Soil description which subsequently feeds into scientific soil classification, can be quite discouraging primarily due to highly diversified national soil classifications, complexities of developed soil taxonomies, ambiguities, tedious and costly diagnostics, complicated and confusing jargons (Krasilnikov et al., 2010). Farmers fertility indicators are holistic while scientific indicators are generally reductionist, although now shifting towards more holistic assessment (Kelly & Anderson, 2016). Harmonizing of the two knowledge systems is essential to ensure sustainable and productive farming (Corbeels et al., 2000; Kelly & Anderson, 2016; Krasilnikov et al., 2010). Incorporating of scientific soil classification and local knowledge on farming and management practices provides an opportunity for proper land management and resource management (Handayani & Prawito, 2010; Martin & Santos, 2016).

Comprehensive knowledge on soils and soil properties is essential in realizing sustainable land use (Martin & Santos, 2016). The land use framework developed by the FAO provides guidelines for land classification as criteria for land use. However, this process has been accomplished primarily through soil surveys which farmers may hardly fully appreciate and which overlook the social and cultural elements (Buthelezi et al., 2010). Understanding the indigenous knowledge of soils proved a critical ingredient in appreciating the prevailing local realities of the people, and farmers in particular. On one hand, scientists assess land suitability based on parameters that can influence a given land use. Local farmers, on the other hand evaluate land by empirical testing over years of trial and error (Martin & Santos, 2016; McRae & Burnham, 1981).

SOIL FERTILITY MANAGEMENT

Declining soil fertility is a serious problem across sub-Saharan Africa, and a persistent constraint to agricultural production, especially in low potential areas, thus posing a major threat to food security and rural livelihoods (Corbeels et al., 2000; Onduru et al., 2001; UNDESA, 2013; Vanlauwe et al., 2017). Many studies indicate that some soils are losing their capacity to provide food and other essential ecosystem services especially in Africa (Ajayi, 2007; Bado & Bationo, 2018; Heerink, 2005; Kiboi et al., 2019; Marenya & Barrett, 2007; Sileshi et al., 2019) due to land degradation and fertility depletion. These soils are highly susceptible to erosion because of lack of binding agents such as humus (attributable to low organic matter); they have high phosphorus fixing ability requiring resource poor farmers to apply phosphorus fertilizers more often; and they are generally shallow (e.g. Leptosols) and thus lose soil moisture very easily (Landon, 1991; NAAIAP, 2014). These characteristics explain the low productivity that characterizes African agriculture (Shepherd & Walsh, 2007) and thus calls for urgent and sustainable interventions.

Soil capital is one of the most critical assets smallholder farming communities depend on for food and income. It is thus necessary for the farming households and other relevant stakeholders to invest in the conservation and building up one of their scarcest and most precious assets. Indeed, there has been emergence of a myriad of efforts to enhance crop and livestock production in various parts, especially in sub-Saharan Africa. Integrated natural resources management (INRM) and integrated soil fertility management (ISFM) approaches are among the system technologies that have been developed to enhance soil fertility (Adolwa et al., 2019) and enhance agricultural productivity (Marenya & Barrett, 2007). INRM entails a broad-based management of natural resources including land, forests, water and biological resources in order to realize sustainable agricultural productivity.

Integrated Soil Fertility Management (ISFM)

ISFM is the application of soil fertility management practices and the knowledge to adapt these to the local conditions. It involves simultaneous application of multiple practices in managing soil fertility in an integrated formula to harness from the complementarities among the management practices (Marenya & Barrett, 2007). TIt includes the limited and smart use of inorganic fertilizers, application of manure and improved crop varieties, the conservation of soils and their biota coupled with the know-how to adapt these practices to local environment for optimal output and agronomic efficiency of the supplied crop nutrients (Sanginga & Woomer, 2009; Vanlauwe, Bationo, Chianu, et al., 2010). ISFM is built on the philosophy that no single soil fertility management technique can stand on its own in satisfying the requisites of increased soil fertility management (Marenya & Barrett, 2007; Place et al., 2003), and that some practices, such as fertilizer type, are site-specific (Adolwa et al., 2019). The ISFM approach proposed by Vanlauwe et al. (2010) demonstrates that progressive adoption of combination of practices has the potential to maximize agronomic use efficiency of the applied nutrients and enhance agricultural productivity, attributed to complementarity effects of management practices such as organic manure and mineral fertilizers accompanied with sound husbandry practices (Mponela et al., 2016).

The ISFM approach challenges a long-held belief that mineral fertilizer is the cure to all soil fertility issues (Vanlauwe et al., 2014). The attractiveness of a given set of ISFM technologies, however, is highly dependent on the nature of the field (responsiveness to fertility techniques). Poorly responsive and severely degraded fields for instance, would require long-term rehabilitation with gradual application of manure to restore soil fertility and enhance efficient uptake of nutrients by crops. This, however, implies a longer period required for SOC build-up, the waiting which most farmers cannot afford considering their conditions. Farmers are largely driven by short-term benefits. Nevertheless, mixed crop-livestock farming systems which are common among smallholder farmers provide good opportunity for application of ISFM principles. The framework's tenets provide for the strategic application of manure and mineral fertilizer within smallholder farms based on the responsiveness patterns of different fields to ensure maximum marginal returns to investment (Tittonell et al., 2008).

However, adaptation of the various fertility management techniques appears to be a challenge as demonstrated by low adoption (Yengoh, 2012). Evidence suggest that farmers adoption of technologies vary based on a range of socio-economic, biophysical and institutional factors (Asrat et al., 2004; Nigussie et al., 2017) as well as knowledge and skills on best agricultural practices (Muhanji et al., 2011). Generally, the low adoption of agricultural technology among smallholder farmers in SSA has been attributed to lack of enabling resources (Mugwe et al., 2009; Shikuku et al., 2017) including physical and capital endowments (Gebremedhin & Swinton, 2003; Marenya & Barrett, 2007; Pender & Gebremedhin, 2008; Teklewold, 2016; Teshome et al., 2016) such as land (Adimassu et al., 2016), size of livestock units (Adimassau et al., 2014; Asrat et al., 2004; Pender & Gebremedhin, 2008), agricultural extension services (Paudel & Thapa, 2004) and credit(Tiwari et al., 2008). Other determinants include family size and on-farm labour (Adimassau et al., 2014; Asrat et al., 2004; Pender & Gebremedhin, 2008).

Fertilizer and manure use among smallholder farming systems

Combination of mineral fertilizer and manure which constitutes one of the strategies promoted under the concept of integrated soil fertility management (ISFM), provides a practical solution to soil fertility challenges and a pathway to sustainable agricultural intensification. Targeted fertilizers are strategically used alongside manure to ensure fertility input efficiency and crop productivity (Tittonell et al., 2008). This strategy has been supported by African governments through the Abuja Fertilizer Summit, whose focus was on maximizing efficiency and profitability of external inputs (Vanlauwe et al., 2014). Integration of minimal amount of mineral fertilizers while capitalizing on organic resources, is a requisite for sustained agricultural productivity. Combination of cattle manure with small amounts of inorganic N fertilizer (30kg/ha) increased grain yields of maize (H513) up to 3 times in on-station experiment on humic Nitisols in Meru (UM 2) (Mucheru et al., 2003).

Whereas mineral fertilizers provide higher nutrients to the soil, manure and other organic resources are critical in raising soil organic matter, giving the soil the desired firm structure and ensuring sustainable productivity. For most farmers, manure is the first source of farm fertility. However , manure application in SSA is constrained by limited availability and poor quality (Adimassu et al., 2016; Chianu et al., 2012; Druilhe & Barreiro-Hurlé, 2012; Ndambi et al., 2019). The scarcity of organic resources is attributed to smallholder farmers low resource endowment (Vanlauwe et al., 2014; Vanlauwe & Giller, 2006). The farmers own a small number of livestock with different livestock management practices such as stall feeding and free grazing system. In some cases, free grazing happens on communal fields which does not support accumulation of enough manure on household's farm (Bindraban et al., 2018; Waithaka et al., 2007).

Low quality of organic resources is attributed to poor manure management practices (Ndambi et al., 2019). The nutrient composition of the organic inputs and the rate of release of these nutrients to plants are largely determined by the quality of organic resources based on their chemical characteristics. Compared to fertilizers, relatively large amount of organic inputs is required (6-8 tonnes/ha) to release the required amount of nutrients (NAAIAP, 2014). However, the application rate is less than 2.0 ton/ha and the average livestock ownership in this region is estimated at 3 cows per household (Jaetzold et al., 2007a). Realistically, therefore, the organic resources applied hardly release sufficient nutrients to match the nutrient required for optimum crop yield (Makokha et al., 2001). For instance solid cattle manure (the most common type of manure) produces about 2-7.7 N, 0.5-2.5 NH_4^+-N, 1.0-3.9 P_2O_5, 1.4-8.8 K_2O, and 0.7-2.1 kg of Mg per ton of fresh matter (Ndambi et al., 2019). The high variations in nutrient content is as a result of different management regimes including animal diet, how manure is collected, stored and handled (Mucheru et al., 2003; Ndambi et al., 2019). On the other hand, due to the high element concentration and high solubility of the mineral fertilizers, their beneficial impact is almost immediate. Nevertheless, organic fertilizer is generally stable and not so much threatened by outwash or insoluble fixation(Jaetzold et al., 2007b). It thus follows that addressing soil fertility management requires taking into consideration the overall land management issues (Corbeels et al., 2000) to facilitate tailored solutions based on local needs and resources.

The low fertilizer use that characterizes SSA farming systems has been attributed to a number of factors including high importation cost, poor infrastructure, high tariffs and small, weak and fragmented markets (Chianu et al., 2012). Other constraints include farmers' lack of knowledge on the use of fertilizers, low literacy levels and poor cultural practices (Makokha et al., 2001). Inappropriate fertilizer packaging sizes, poor quality of supplied fertilizers, untimely availability, poorly managed or lack (or removal in some cases) of input subsidy programs, weak agricultural extension and soil science capacity have equally contributed to low intake (Chianu et al., 2012). Some of the government's subsidy programs, in Kenyan case for example, remain regressive and distortionary (Birch, 2018). However, this year's launch of the e-voucher system, a digital platform that involves a partnership between the government and commercial banks and agro-dealers, is expected to enhance the program's efficiency (IFAD, 2020; Xinhua, 2019).

The soil fertility question is a complex one, requiring a precise approach. Some soils suffer from low nitrogen and phosphorus levels, thus there is a need for increased use of inorganic fertilizers and organic resources to boost land productivity (Makokha et al., 2001). Kenyan soils lack major macronutrients (N and P) as well as micronutrients such as zinc and sulphur (Kibunja et al., 2017). The use of fertilizers has been shown to sustainably increase crop yields by 50-100%, thus significantly bridging the gap between the actual farmers' yields and the potential possible yields based on on-station research trials (Chianu et al., 2012). However, appropriate application of inputs is critical for both economic (productivity) and environmental sustainability (Vanlauwe, et al., 2011). 'Appropriate' implies applying the right type of input, at the right time, at the right rate and place (Vanlauwe, et al., 2014). it also means avoiding non-responsive soils (Rusinamhodzi et al., 2013).Caution should thus be exercised to avoid overapplication and the use of inappropriate fertlizers which can lead to pollution and destruction of soil biota.

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2.5 Farm Management Practices and the Influence on Soil Fertility

2.5.1 Overview

Agricultural production systems are affected by complex interactions between social and ecological factors, which are difficult to integrate in a common analytical framework. These interactions and diversity are particularly strong in smallholder farming systems in sub-Saharan Africa which occur within diverse biophysical and socio-economic environments. In many regions of sub-Saharan Africa, smallholder farms exhibit a large degree of soil heterogeneity, which is the result of the inherent soil-landscape variability plus the effect of past and ongoing soil management (Tittonell et al., 2015). The status and variability of soil fertility within smallholder farms are likely to vary between households of different socio-economic status, or between those pursuing different farm objectives (e.g. market orientation vs. subsistence) (Rapsomanikis, 2015; Tittonell et al., 2010). Within individual farms, resource limitation forces farmers to preferentially allocate available labour and nutrient resources to certain fields, which contributes to the creation of spatial soil variability(Tittonell et al., 2005).

Farmers adopt different technniques of management practices to meet their production needs. The decision to adopt (or not to adopt) these technologies is often influenced by various factors including financial resources, technical capacity and compatibility with the social, physical and cultural environment. Preferences for a particular set of technologies can be explained by the intention of the farmer to address a specific constraint (Mponela et al., 2016) such as coping with rainfall and climate variability, rehabilitating depleted soils in areas with prevalent soil erosion (Ngetich, 2012). The most common management practices employed by farmers in Mount Kenya region are described in the next section.

2.5.2 Organic and inorganic fertilizer

Fertilizer refers to any inorganic or organic material (either natural or synthetic) that is added to soil or other growing media to supply plant nutrients. Fertilizers may be in solid, liquid or gaseous forms. Inorganic (mineral) fertilizers are derived from ores, air, sediments or ashes. Organic fertilizers are derived from organic materials, including animal or human waste and composit (Chianu et al., 2012).

The most commonly used organic fertilizers in replensishing soil fertility include animal manure (e.g. cattle, goat, sheep, poultry, pig), crop residue (such as maize stover, bean trash, napier grass cuttings, tree/hedge cuttings) bone mean and compost (Mucheru et al., 2003).

Others include, herbaceous legumes which are commonly used as green manure in Kenya. Usually, the legume is grown in pure stand and cut just before full bloom (or flowering stage), while the N content is at or near the maximum. After wilting the leaves, the green manure is incorporated with the soil to facilitate decomposition (Jaetzold et al., 2007). The nutrient contents in manure vary enormously depending on the source, method of processing, application and storage.

2.5.3 Agroforestry

This is the practice of establishing of trees, bushes and shrubs by the farmers on the agricultural farm. The benefits of this system include fruits (or nuts), green manure, fodder fuel wood, timber, fodder and medicine (Jaetzold et al., 2007). In the Agro-Ecological Zones (AEZ) 1–3 it can replace partly the forest ecosystem, which was the natural climax vegetation. An AEZ refers to a zone defined by its relevant agro-climatic factors (in the Tropics mainly moisture supply) and differentiated by soil pattern. The AEZ of the tropics include 0 (perhumid), 1 (humid), 2 (subhumid), 3 (semi-humid), 4 (transitional), 5 (semi-arid), 6 (arid) and 7 (per-arid). The agro-ecological zones of the tropics (Jaetzold & Schmidt, 1983). However, caution should be exercised when implementing this farm management system because some crops (such as maize) require optimal light conditions. Vegetables on the other hand, require less light and can therefore be easily be grown in the shade and combined with higher plants. Due to competion for water and plant nutrients, trees species should be carefully considered. Some of the recommended agroforestry include macadamia nuts, mangoes, Grevillea robusta and Melia volkensii (Jaetzold et al., 2007).

2.5.4 Fallowing

Fallowing allows for the regeneration of soil fertility. Improved fallow systems which require shorter periods than the coventional fallow is a quick way to revitalize soil, and highly recommended. Fast growing nitogen fixing plants are often used. In addition, besides N, other limiting nutrients (such as K and P) can be added to highly degraded soils during improved fallow. In Western Kenya, higher economic returns for maize and beans were registered in the improved fallow (with Crotolaria gramiana or Tephrosia vogelii) than where natural fallow was used (Muriuki et al., 2001).

2.5.5 Organic resource management practices (conservation tillage)

Besides the application of manure, smallholder farmers in Kenya apply various organic input management strategies including mulching, minimum tillage and crop residue retention. These interventions improve soil organic matter, moisture content and aid in maintaining the desired soil nutrient status. Mulching is the artificial application of mulch (including crop reidues) with the aim of obtaining favourable changes in the soil environment. Minimum (also known as zero or reduced tillage) is a form of conservation tillage aimed at keeping tillage practices at the possible minimum while maintaining surface residues at at least 30% of the soil surface (Parr et al., 1990). Minimum tillage system of cultivation and crop residue mulches form a basis for conservation farming because they conserve water, prevent erosion, maintain organic matter and sustain economic productivity (FAO, 1991).Crop residue management and conservation tillage practices are crucial components in soil and water conservation, especially in semi-arid regions (Opara-Nadi, 1993) such as parts of Tharaka Nithi county

3 MATERIALS AND METHODS

This section describes the study area in terms of its physical location, climatic patterns, demographic and socio-economic characteristics. This is followed by the sampling design, which describes the methodology used in determining sampling sites as well as the methods used in obtaining social data and soil samples. Laboratory analyses protocols for the various soil attributes are explained. Finally, the statistical and qualitative analyses used are discussed.

3.1 Description of the Study Area

The study was conducted in Mount Kenya East, a region encompassing Meru and Tharaka Nithi Counties (Figure 3.1) covering an area of 1,618 km^2within longitudes 37°53'38.4" E and 37°33'35.28" E and latitudes 0°4'26.4" N and 0°20'20.4." S. The counties are located almost in the middle of the country, on the eastern slopes of Mount Kenya, about 200 km north of the Kenyan capital, Nairobi. The primary land use is rainfed agriculture.

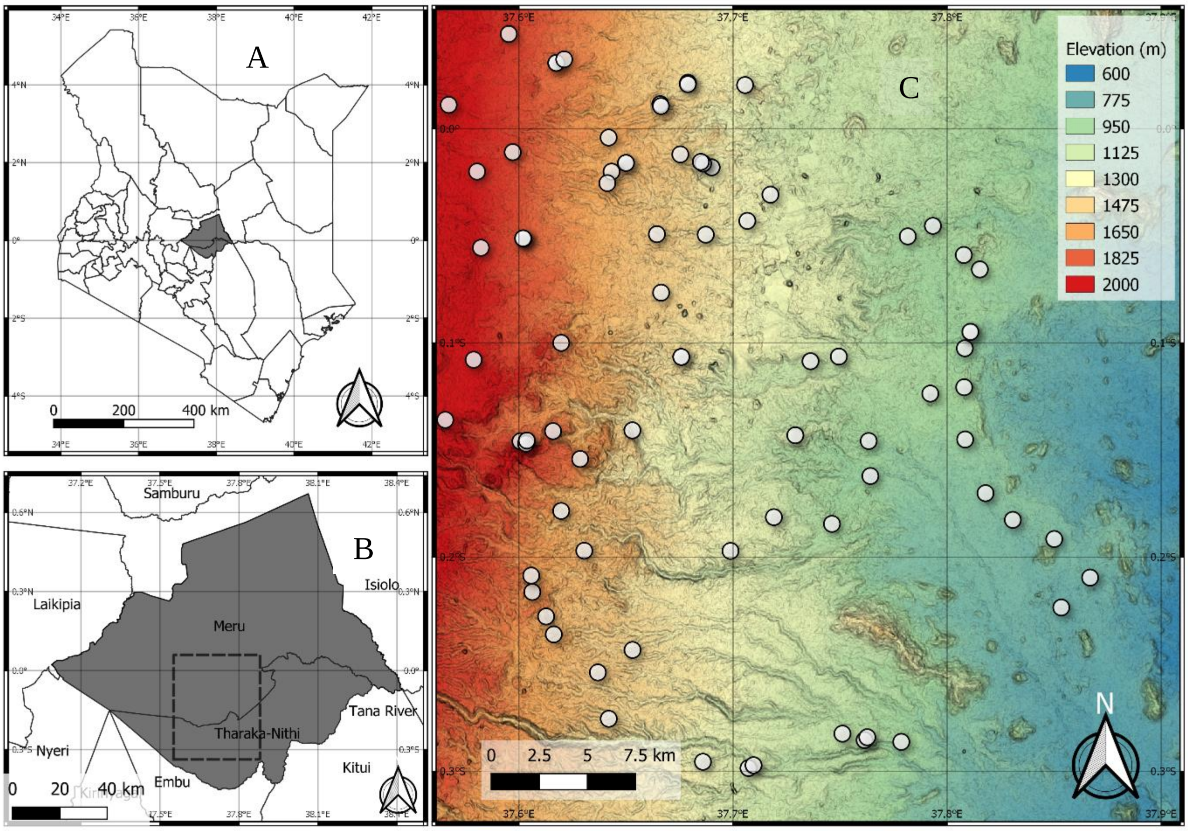

Figure 3.1. Map of Kenya (a) showing the Location of Meru and Tharaka Nithi Counties (b), and the distribution of sampling points within the study area (c)

Meru's total land area is about 6,936 km^2, of which more than a quarter is protected forests. The population of the area based on the 2009 Kenya's population and housing census stood at 1,545,714 people with 426,360 households. Human development index is estimated at 0.57% slightly higher than the national average of 0.56%. With a land area of 2,662 km^2, Tharaka Nithi County populationhas a population of 393,177 people, with Human development index of about 0.55%, which is slightly lower than the national average of 0.56% (CIDP, 2018).

This relatively dense population of 221 and 153 persons per square km, in Meru and Tharaka Nithi derives their livelihood from farming and has put a lot of pressure on land leading to overexploitation of natural resources and advanced land degradation, especially in potentially high productive areas. Agriculture dominates the region's economic activity and accounts for 80% of the economy, with more than 90% of the population directly or indirectly dependent on farming. Majority of the farmers are smallholders, constituting about 98.6% of farms. The average farm size is estimated at 2 acres (in Meru) and 2.9 acres (Tharaka Nithi), but this varies based on population density (County Government of Tharaka-Nithi, 2013; Meru County Government, 2014). In Meru County, the average farm size ranges between 0.2 ha (in the densely populated tea/dairy zones) to 2 ha in the lower midlands (CIDP, 2018). The average farm size in Tharaka Nith ranges between 2 ha (in the densely populated areas including Meru South and Maara sub-counties) to 5 ha, in the sparsely populated areas such as Tharaka sub-County (County Government of Tharaka-Nithi, 2013). The region experiences shortage of farm labour and rising unemployment rate due to the youth's preference for white collar jobs in an otherwise predominantly agriculture-based economy (CIDP, 2018; County Government of Tharaka-Nithi, 2013).

Climate

The region is characterised by a bi-modal rainfall pattern, with longer rains occurring between March-May, and the shorter rains between October-December. There is high variation in rainfall which increases from east to west, with the annual mean rainfall ranging from 300 mm to 2,500 mm. The region's altitude spans from 300 metres (low hills) to 5,199 metres (the peak of Mt. Kenya) above sea level. Temperatures range between 8°C and 32°C (CIDP, 2018; County Government of Tharaka-Nithi, 2013)..

There are primarily two landforms in the area: uplands with gently undulating to rolling landscape (slope ranging from 2-16%), and minor valleys with 5-30% slopes (undulating to hilly). In some places, the valleys are deeply incised (Mason & Geological Survey of Kenya, 1955; Njoroge & Kimani, 2001)

Tharaka Nithi County is located in the Upper Midland Zone two (UM2) and Upper Midland Zone three (UM3) agro-ecological zones (AEZ) on the eastern slopes of Mount. Kenya. Meru comprises of about twenty different sub-Agro-ecozones (CIDP, 2018), falling into four main agro ecological zones (AEZs) ranging from the upper highlands-UH3 to lower midlands-LM6 (Jaetzold et.al., 2010).

The region's varied climatic and ecological zones is the basis for its diverse agricultural production, which is primarily rainfed (County Government of Tharaka-Nithi, 2013; Meru County Government, 2014).

Agriculture

The study area is characterized by a wide range of socio-economic and biophysical conditions, which is typical of highlands, midlands and lowlands where both mixed farming and agro-pastoralism are common.

The crops grown range from staples, cash and horticulture crops. Food crops grown include white corn (maize), beans, bananas, sweet potatoes, Irish potatoes (potatoes), peas, cowpeas, arrow roots, yams. Horticultural crops include fruits (such as mangoes, passion fruit, avocadoes, watermelon, nuts and pineapples), vegetables (such as snow peas and French beans) and flower farming (cut flowers). Coffee and tea are the main cash crops (CIDP, 2018; County Government of Tharaka-Nithi, 2013).

Livestock farming is equally an important means of livelihood, with exotic dairy cattle (Meru-114,251, Tharaka Nithi- 32,634), exotic beef cattle (Meru-24,656, Tharaka Nithi-5,137),indigenous cattle (Meru-173,277, Tharaka Nithi-52,935), goats (Meru-342,198, Tharaka Nithi-214,217) andsheep (Meru-138,771, Tharaka Nithi-53,816) being the most important livestock in the region. Chicken, both indigenous (Meru-1,006,744, Tharaka Nithi-418,193) and exotic (Meru-210,034, Tharaka Nithi-42.661) are the most common poultry (KNBS, 2019). Livestock is also an important source of manure. The community also derives livelihood from lumbering. *eucalyptus*, *cypress* and *Grevillea robusta* are the major trees used for timber, fuel and charcoal (CIDP, 2018; County Government of Tharaka-Nithi, 2013). .

Geology and geomorphology

The geology in the area is primarily volcanic rock, ash and old metamorphic rocks (Schoeman, 1952). The Mount Kenya volcanics consist of basalts, rhomb porphyries, phonolites, kenytes and trachytes which make up the main period of eruption. The plug of the volcano consists of nepheline syenite and phonolite in the form of a ring structure. Satellite activity from fissures resulted in the eruption of further phonolites, basalts, trachytes and mugearites, and the activity on the mountain was brought to a close by further satellite eruptions of trachytes, pyroclastics, basalts, and basaltic pumice from various vents on the slopes of the original volcano. The Mt. Kenya volcanics are believed to be mainly of Pleistocene age (Baker, 1967)..The soils around the area are mainly developed from basalts of Mount Kenya volcanics (Njoroge & Kimani, 2001).

Major soil types of study area

There are two major predominant Reference soil groups based on WRB (IUSS Working Group, WRB, 2015), namelyNitisols and Acrisols, occuring in the uplands and lowlands, respectively. Other common soils include Andosols, Umbrisols, Cambisols and Leptosols (Figure 3.2).

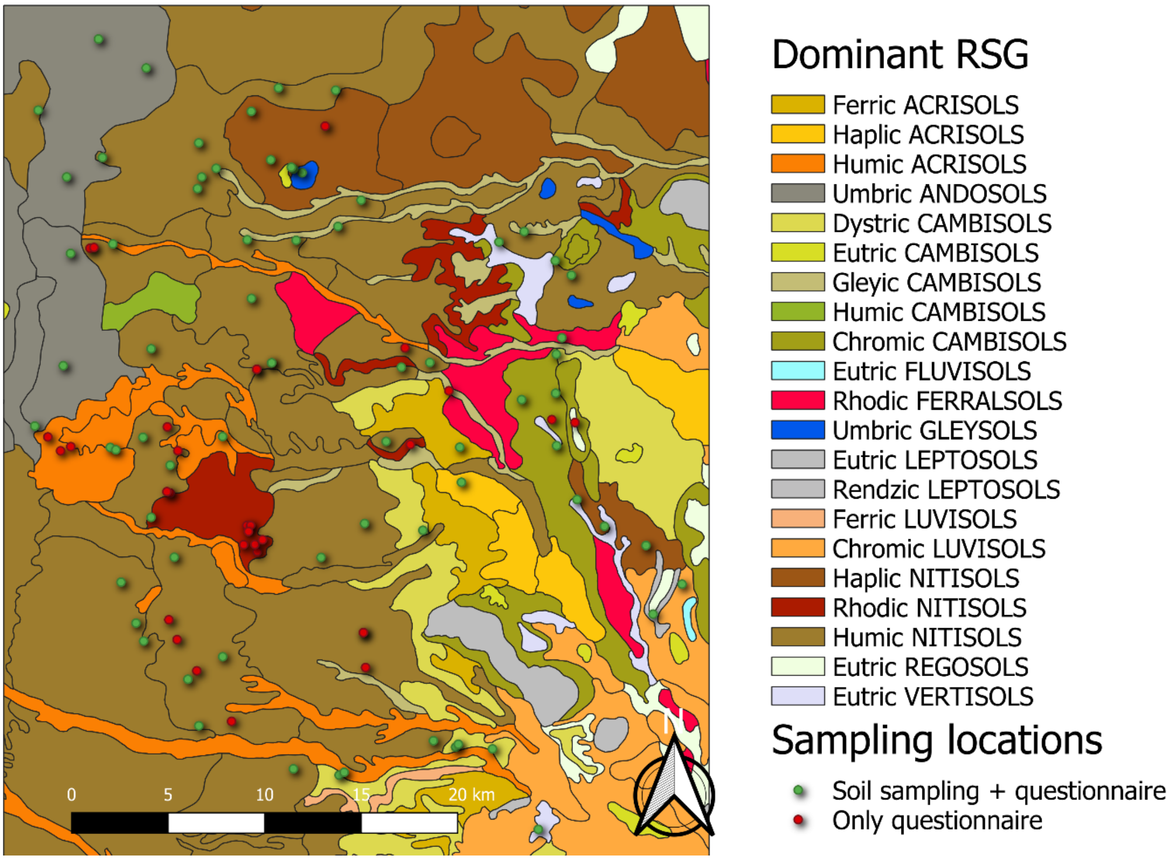

Figure 3.2. Major Reference Soil Groups of the study sites (Source: Dijkshoorn et al., 2011)

The soils in the lowlands (Tharaka-Nithi) are predominantly sandy loam and shallow, thus the need for moisture conservation measures (Muriu-Ng'ang'a et al., 2017).

The study site was mapped using SOTER_UT and ISRIC-WISE, based on 186 unique SOTER units. SOTER_UT, at scale 1:100,000, which is more detailed compared to SOTER databases edition II and I, at scale 1:250,000 and 1:1 M, respectively (Dijkshoorn et al., 2011). Individual map units comprising of up to four different soil compinents were characterized by a regionally representative profile, identified and classified by national experts. Characterization was based on

144 profiles (108 real profiles, and 36 synthetic profiles), and taxotransfer procedures used to fill the gaps in the analytical data to facilitate modelling (Batjes, 2010). Soil property was estimated for 18 soil variables by soil unit for a fixed depth interval of 20 cm to 100 cm depth. The properties include organic carbon, pH(H2O), content of sand, silt and clay, coarse fragments content (>2 mm), base saturation, soil cation exchange capacity(CEC_{soil}), clay cation exchange capacity (CEC_{clay}), effective CEC, total nitrogen, aluminium saturation, exchangeable sodium percentage (ESP), CaCO3 content, gypsum content, electrical conductivity (ECe), volumetric water content. These attributes are considered critical for agro-ecological zoning, land evaluation, simulation of crop growth, carbon stocks modelling, and studies of global environmental change (Batjes, 2010).

3.2 Sampling Design

This section provides a detailed description of sampling methods used in determining locations for soil sample collection and socio-economic data collection. Soil sampling was conducted to facilitate characterization of soils in the study area in terms of determination of soil properties and classification. Soil data was also useful in scientific evaluation of soil fertility or quality (for subsquent comparison with local assessment and correlation with farm management practices). Social survey was aimed at describing farming systems, scocio-economic characteristics, farmers' management strategies and soil fertility assessment systems.

3.2.1 Soil sampling design

Mapping of soil properties and fertility management practices made use of: (a) systematic and unbiased field surveys to collate soil data and other ecological parameters; (b) laboratory analyses using IR spectroscopy and wet chemistry, and (c) remote sensing information (Vagen, Winowiecki, Abegaz, & Hadgu, 2013)

Developing a sampling scheme that as much as possible takes into account variations in soil types and soil properties in the study area was first undertaken. Variation in soil types reflects the natural distribution of soil forming factors and the soil forming processes. The proposed sampling scheme preserves the natural distribution of both the continuous and categorical soil forming factors. To achieve this end, the ancillary data to be used in the sampling design process were assembled. This was guided by SCORPAN model of soil formation (McBratney et al., 2003).

For continuous variables, elevation data derived from Advanced Land Observation Satellite (ALOS) data. The slope was calculated from the elevation, topographic position index, and

Topographic Wetness index. These methods are the most often used due to their efficiency, detail and availability (Weih & Mattson, 2004).

Categorical variables: i) the Parent material layer (geology of the area) generated from a digitized ISRIC document of the study area, was used; ii) SOTER_UT (at scale 1:100,000) polygons soil unit layer were used because of their higher resolution (Dijkshoorn et al., 2011) ensuring the inclusion of all polygons in the sampling exercise. ; iii) the ancillary data was the base for input layers for the conditional Latin Hypercube objective function equation in R programming platform, and GIS interface used to visualize output; iv) The sampling scheme was evaluated to confirm congruence to the natural distribution of the selected ancillary data by use of boxplots.

Conditioned Latin Hypercube **Sampling**

Conditioned (or constrained) Latin Hypercube Sampling (cLHS) aims at creating a dataset that covers the covariate space, while taking unforeseen constraints (such as poor road network, very steep slopes 'unsampleable" or forbidden areas like parks and water bodies) into consideration, and minimizing costs in relation to the sample size, time required for sampling, and accessibility of sampling sites. Covariate space can be defined as the space covered by the covariates utilized by the cLHS (Mulder et al., 2012).

It was necessary to consider the variability of environmental variables, thus the justification for the use of cLHS in our sampling scheme. The following equation (1) by Minasny and McBratney (2006) was applied.

$$J = w1 * \sum_{i=1}^{n} \sum_{j=1}^{k} \left| n_{ij} - 1 \right| + w2 * \sum_{p=1}^{n} C_p \qquad (1)$$

Where;

n - the sample size

k- number of variables (the environmental covariates or soil forming factor derivatives)

n_{ij} - the number of times that an interval i for variable j is sampled,

C_p – cost related with sampling point p

w1 – the relative weight of the cLHS component w2 – the relative weight of the sampling costs

Assemblage of input variables into cLHS Equation

This section describes the processing of environmental variable layers as well as the operational cost layer for the cLHS algorithm. The layers were generated as input variables for the cLHS equation. The digital soil mapping formula proposed by McBratney (2003), and presented in Equation (2), was taken into account.

$$S = f\ (s,c,o,r,p,a,n) \tag{2}$$

Where: s = soil attributes or classes, c=climate, o=organism, r= relief, p= parent material, a=time/age, n = spatial location or position. These factors influence the formation of soil at a given point, and can be used to predict soil map. Unlike *clorpt*, the *scorpan* model is intended for quantitative spatial prediction, and not just explanation (McBratney et al., 2003).

Further parameterization of other soil forming factors are described in the subsequent sections.

Topographic Wetness Index

Also known as Compound Topographic Index (CTI), *Topographic Wetness Index* (TWI) refers to a steady state wetness index, commonly used to quantify topographic control on hydrological processes. TWI is a function of slope and the upstream contributing area per unit width orthogonal to the direction of flow (Sørensen et al., 2006). Calculation of TWI is as shown in equation (3)

$$TWI = ln\frac{a}{\tan b} \tag{3}$$

Where:

a is the local upslope area draining through a given point per unit contour length and is expressed in square metres (a =A/L, catchment area (A), contour length (L)). tan b is the local slope in radians (Gessler et al., 1995; Hojati & Mokarram, 2016). TWI has no units.

The TWI of the study area ranged between 3 and 11 (Figure 3.3). High values of TWI imply high runoff potential.

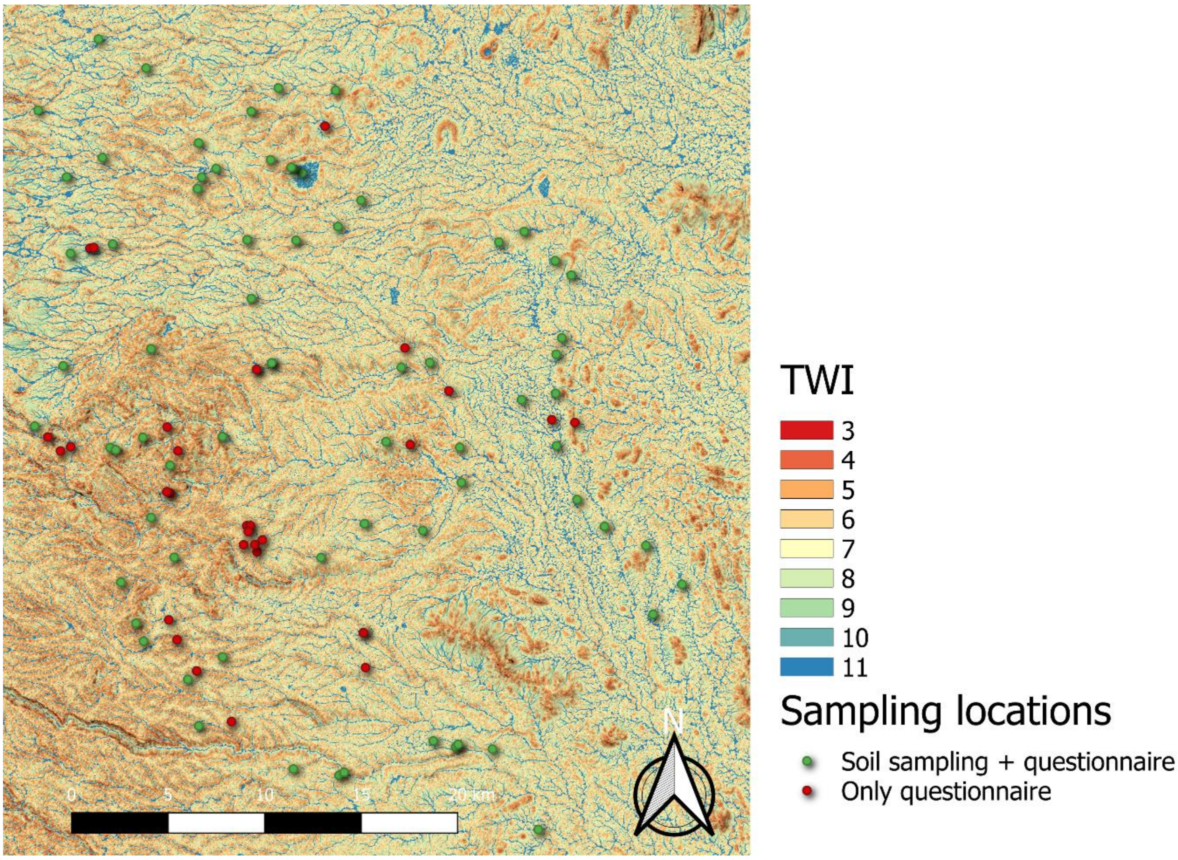

Figure 3.3. Topographical Wet Index of the study area

TWI helps in forecasting the amount of moisture in the soil (Hojati & Mokarram, 2016), thus justifies its inclusion in the cLHS algorithm. It accounts for spatial variation in hydrologically relevant soil properties (Hojati & Mokarram, 2016)

Steps in creating TWI: go to SAGA GIS module > Terrain Analysis >Hydrology > SAGA Wetness Index.

Slope algorithm

To parameterize relief, landform and slope classes extracted from DEM were taken as the indicator(Alijani & Sarmadian, 2013). The slope (in DEM) is the function of gradients in the X and Y direction (4)

$$\text{Slope} = \arctan\sqrt{(fx)^2 + (fy)^2} \quad (4)$$

Most importantly in estimating the slope is the computation of the perpendicular gradients fx and fy (Tang & Pilesjö, 2011). The study area landforms were separated using SAGA (2.0.8) software based on topographic position index (TPI) classification (Alijani & Sarmadian, 2013). Slope was calculated as local slope around the pixel. The TPI compares the elevation of each cell in a DEM to the mean elevation of an identified neighbouring cell. Higher locations (ridges) are represented by positive TPI while valleys are represented by negative TPI. Zero TPI values indicate flat areas(Alijani & Sarmadian, 2013). Slope percentages determine the rate of deposition of soil material, thus constitutes a vital variable candidate for cLHS algorithm input. The slope of the study area ranged between 1% and 69% (Figure 3.4).

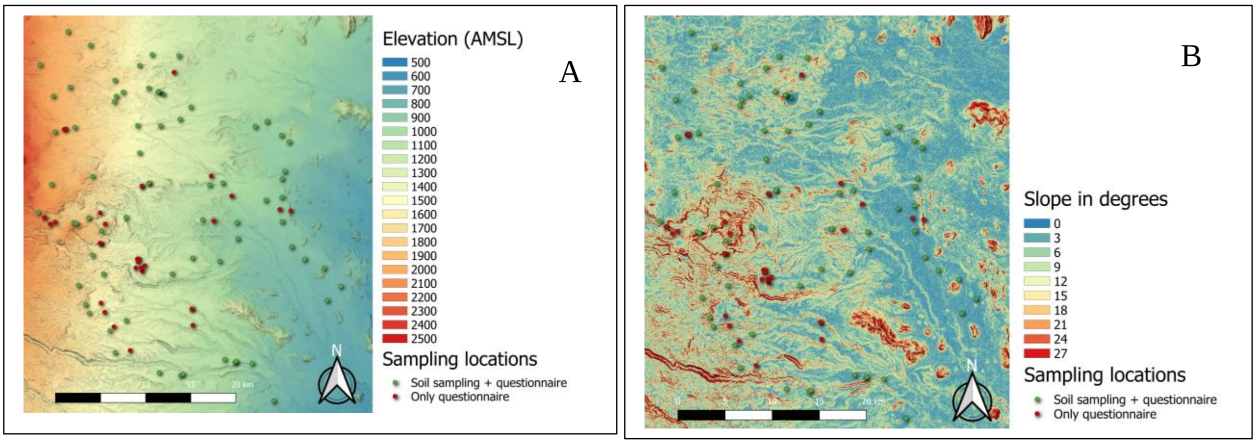

Figure 3.4. Elevation (A) and Slope (B) of the study area

Calculating the operational cost layer

Operational cost layer refers to a built-in function in cLHS algorithm that strives to answer such question as, "how long will it take me to move from point A to B?" Based on cost, we are able to constrain the points to particular locations. For example, the cost constraint is useful in avoiding forbidden sites (such as parks), inaccessible points (due to impassable roads), or too rugged terrains. In this case, a cost raster where larger pixel values are "more expensive" to visit. The 'ease of reach' points were determined by generating a "cost of reach" layer(Roudier et al., 2012). The cost raster (or travel model) was created in SAGA using the Accumulated Cost (Anisotropic) function with distance from the road network to the destination as a roads grids, and slope percentage (also known as "friction") as the cost grid, and aspect as the direction grid. The cost of reaching a given point is given by Equation (5)

$$M_{cost}(k) = \left| e\left(-\frac{\Delta_{cost}(k)}{T}\right) \right. \quad (5)$$

Where: Δ_{cost} (k) = cost (k) – cost (k -1), the cost variation of the candidate sampling scheme between iterations k – 1 and k. cost (k) is the sum of the cost (x, y) layer values at the locations of the sampling scheme at the iteration k. The input of operational cost layer in the cLHS increases reachability of most of the sampling points (Roudier et al., 2012).

Summary of soil sampling design

cLHS is a type of stratified random sampling that accurately represents environmental covariates variability (Brungard & Boettinger, 2010). Relief was represented by terrain derivatives (slope and TWI); parent material was represented by geology. Due to foreseen constraints such as steepy and rugged landscapes, inaccessibility of some sampling points (due to undeveloped road network), an additional input in the model, namely, operational cost, was necessary. Taking into account all the mentioned covariates, the cLHS model selected 100 sampling points. Further, due to time and budgetary constraints, only 69 points were visited for the actual sampling.

3.2.2 Designing of Farm Household survey and interviews

Quantitative and qualitative social data were obtained through questionnaire survey (Appendix A) and interviews (Appendix B and Appendix C). Questionnaires were administered to 106 pre-selected purposively sampled farmers. The sample size of participant farmers for questionnaire survey was determined using Slovin's sampling formula presented in Equation (6).

$$n = \frac{N}{1 + Ne^2} \quad (6)$$

Where: n = Sample size; N = Total population; e = error tolerance (5%).

By taking into consideration, confidence levels and margin of error, Slovin's formula ensure sampling of a population with a desired degree of accuracy. Slovin's formula of determining sample size is appropriate for a large population with unknown variability (Israel, 1992).

The first 69 respondents were the farmers whose farms had been selected for soil sampling, based on the cLHS design described earlier. The target respondents (sampling unit) were the household heads or the person responsible for farm management decisions.

Interviews were administered to strengthen the quality of questionnaire data (Patton, 2002). This was achieved by interviewing seven (7) extension providers and nine (9) farmers. Five of the seven extension staff were drawn from County government agricultural officers. The other two were Tea Extension Service Assistants from Kinoro and Imenti tea factory. Purposive sampling method was used for the selection of interviewees. While selection of extension personnel was based on availability, the choice of farmers for interview was based on the recommendation of the extension workers within their jurisdiction.

3.3 Field Work and Data Collection

Field work involved soil sampling and collection of social data (through administration of questionnairre and interviews. Figure 3.5 shows the distribution of sampling sites.

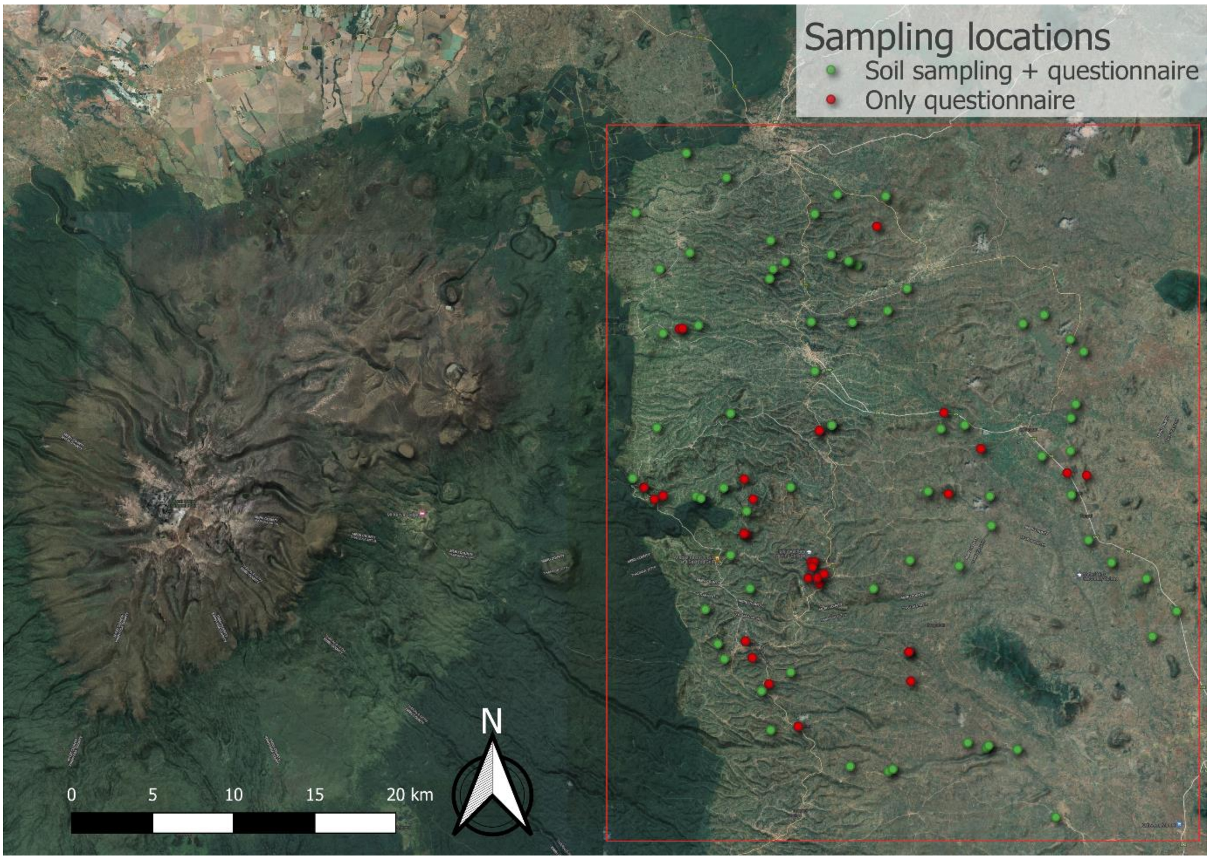

Figure 3.5. Map of the study area showing selected sites for soil sampling and social data survey

3.3.1 Soil sampling

Prior to actual soil sampling, a preliminary reconnaissance field work was undertaken between December 2017 and January 2018. Soil samples were collected from 69 locations (mainly agricultural farms) between January 9 and January 19, 2019. The sampling points were guided by conditioned Latin hypercube sampling design. The field work tools that were availed during the exercise included augers, handles and extensions, shovels, tape measure, plastic sampling bags, Global Positioning system (GPS), pH meters, Munsell colour charts, bucket, 10% HCl acid, labelling pens, spraying bottles, distilled water, FAO Soil Description Guideline and WRB guideline. Before sampling any given point, the following data was recorded: GPS coordinates, locations (County, Ward, and village name), land use and farmer's identity.

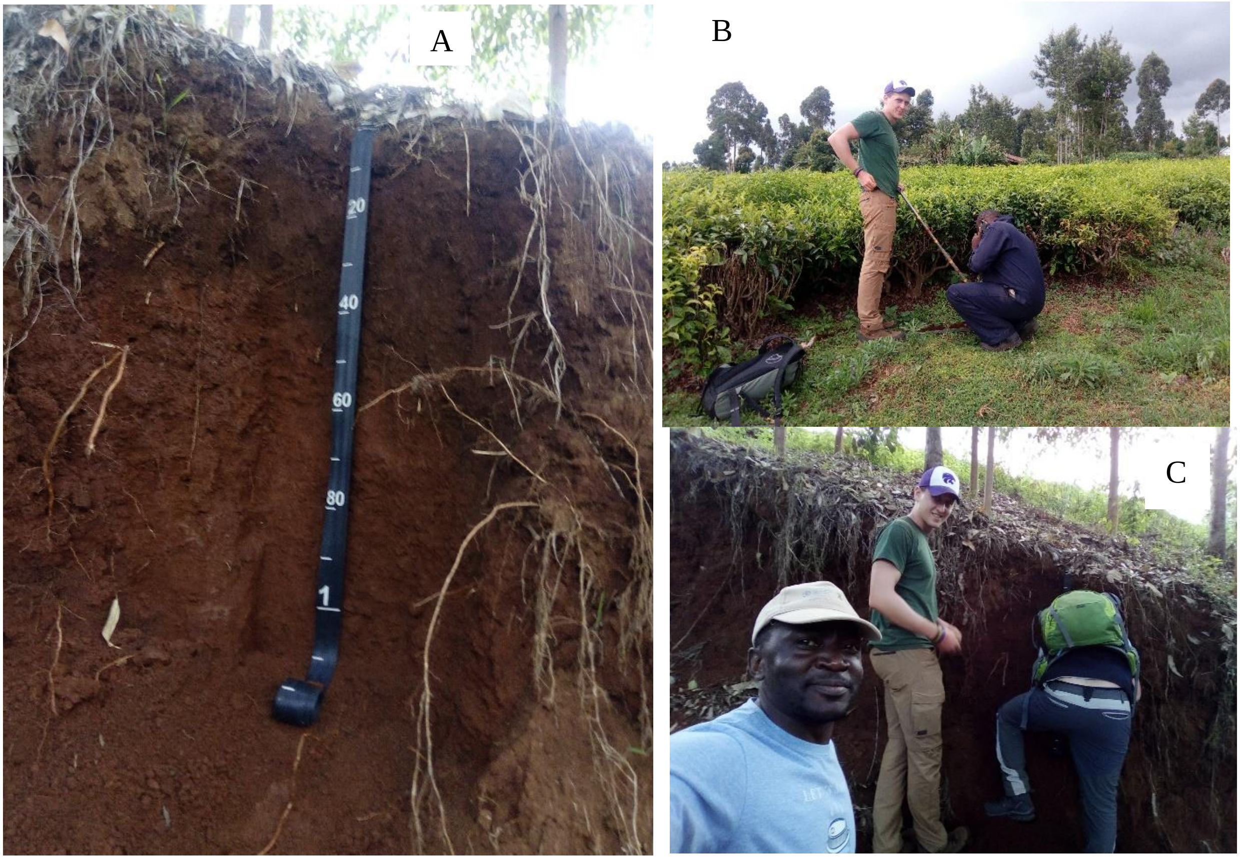

Figure 3.6. Soil sampling: a cleaned open soil profile (A), collection of soil samples through augering (B); obtaining of samples from an open profile (B).

Three samples were obtained from each sampling point at three depth intervals, namely 0-20 cm, 20-50 cm and 50-100 cm, by hand auguring (Figure 3.6). In total, about 207 samples were collected. This design conforms to the approach recommended by the Africa Soil Information Service (AfSIS) of 0-20 and 20-50 cm depth. An additional subsoil sample (50-100 cm) was obtained following the previous sampling designs (Gicheru & Kiome, 2000; Mutuma, 2017). A preliminary field diagnostic and definition of soil properties was performed based on WRB 2014. The initial definition was based on the captured recorded data including, master horizon, depth, Munsell colour, pH, structure, consistency, plasticity, stickiness, and texture.The samples were transferred in properly labelled plastic bags for identification (e.g. 001, 0-20cm). Large clods of soil were broken up to facilitate faster drying. Visible plant residues were removed. The samples were then air-dried. As recommended, drying was done by spreading each sample on a paper to air dry at room temperature (USDA, 2018) for a couple of days. Laboratory colour determination of both dry and moist samples was performed using the Munsell colour chart. The samples were then crushed using a pestle and mortar, and passed through a 2mm-mesh sieve for subsequent laboratory procedures.

3.3.2 Questionnaire survey and interviews

Questionnaire (Appendix A) and interviews (Appendix B and Appendix C) were conducted in two phases: 9th to 19th January and 18th February to 1st March 2019, and were administered through face-to-face survey (Figure 3.7). Data collected by the questionnaire include demographic and socio-economic characteristics (such as education, household farm size), type of farming, the kind of cultivated crops, types and quantity of each livestock, soil fertility management strategies, data concerning fertilizer and manure use (type and sources, frequency of application, beneficiary crops). The questionnaire also assessed farmers' soil fertility knowledge, perceived constraints to soil fertility and farmer's access to agricultural information.

Figure 3.7 Administering farm household questionnaire to a farmer. Photo taken during the survey for this study in January 2019.

Interviews with farmers (Appendix B) focused on household's demographic and socio-economic data, farming enterprises, soil fertility management practices and access to agricultural information, while interviews with extension officers covered the themes on agricultural activities in the area, information delivery and access, soil information and fertility and agricultural incentives (Appendix C). They were conducted face to face and by phone and lasted an average of 40 minutes. Notes were taken during each interview and some interviews were also recorded. Based on the notes and recordings, summaries were prepared for further analysis.

The questionnaire survey and interviews were carried out following the main ethical principles of social science research and an informed consent was obtained from the participants in each case. The fieldwork was approved by the Ad Hoc Ethical Committee of the Doctoral School of Environmental Sciences of Hungarian University of Agriculture and Life Sciences, Hungary, in accordance with the Code on Research Ethics of the Hungarian Academy of Sciences, and the European Code of Conduct for Scientific Integrity.

3.3.3 Laboratory measurements

This section describes the laboratory protocols used for analysing various soil properties. They include analysis for soil organic carbon (SOC), pH, particle size distribution (clay, silt, sand), cation exchange capacity (CEC), exchangeable cations (Ca, K, Mg, Na,). Other measurements obtained from analyses include Base saturation (BS) and texture. Available nutrients were also determined, including, phosphorus (P), potassium (K) and available nitrogen (TN). Soil colour was determined using the Munsell colour chart. Analysis of the various soil properties was critical in addressing objectives one, three and four of this research.

All the soil analyses were carried out in Hungarian University of Agriculture and Life Science laboratories in Gödöllő. In the laboratory, the soil samples were air-dried for a couple of days (USDA, 2018) and passed through a 2mm-mesh sieve.

Soil organic carbon was determined following the Walkley-Black procedure (van Reeuwijk, 2002). Soil CEC and base saturation were determined following the $BaCl_2$ Compulsive Exchange Method (Gillman & Sumpter, 1986; Ross & Ketterings, 2011). The advantages of this procedure include high repeatability, precision, and its direct measure of the soil's CEC. Exchangeable cations (K, Ca, Mg, and Na) were determined following Mehlich 3 extraction method (Mehlich, 1984). Soil pH in H_2O was potentiometrically measured in the supernatant suspension of a 1:2.5 soil: extractant mixture (Carter & Gregorich, 2008). Soil N was determined using the Parnas-Wagner apparatus, with NaOH as the extraction reagent and Boric acid as an indicator solution using the micro Kjeldhal method (Bremmer and Mulvaney, 1982). Soil available K and P were determined using ammonium lactate acetate solution method (Egnér et al., 1960). The distribution of clay, silt and sand particles was determined by mechanical analysis using the pipette method (Haluschak, 2006).

SOC and pH was measured for all samples. However, only 39 representative samples were subjected to the rest of the laboratory analyses protocols. The selected samples were determined following K-means clustering based on Mid Infrared (MIR) spectra analysis.

3.3.4 Mid Infrared (MIR) Spectra of soil samples

Infrared (IR) spectroscopy (Figure 3.8) provides a unique “chemical overview” of a soil sample with all the chemicals present contributing to the resulting spectrum. The technique which can be applied on both organic and inorganic materials, allows for the qualitative analysis of a large variety of samples ranging biological samples to clay minerals. Expert interpretation of spectra and the use of spectral libraries make it possible to identify the unknowns (The James Hutton Institute, 2020).

MIR identifies the kind of molecular motions and bonds or functional groups present in a sample, because different functional groups absorb at varied frequencies involving different types of chemical bond vibrations (e.g. stretching and bending). Molecules interact with the electric vector of infrared (IR) radiation resulting in absorption at different frequencies. Fourier Transform Infrared (FTIR) spectrum in the MIR region of a soil sample, produced when IR is absorbed by a soil sample, gives the overall chemical profile of the soil. A range of sampling methods can be used in recording FTIR spectra of soil samples, including Transmission, Diffuse Reflectance (DRIFTS) and Attenuated Total Reflactance (ATR). FTIR spectra can provide information about both the organic and mineral components of the soil. Absorption bands in the IR spectrum (4000 to 400 cm -1) explains the fundamental vibrations of the functional groups present in the sample. MIR is considered a powerful tool for soil analysis because of a combination of interpretation of spectra and development of calibrations (Robertson & Pérez-Fernández, 2017).

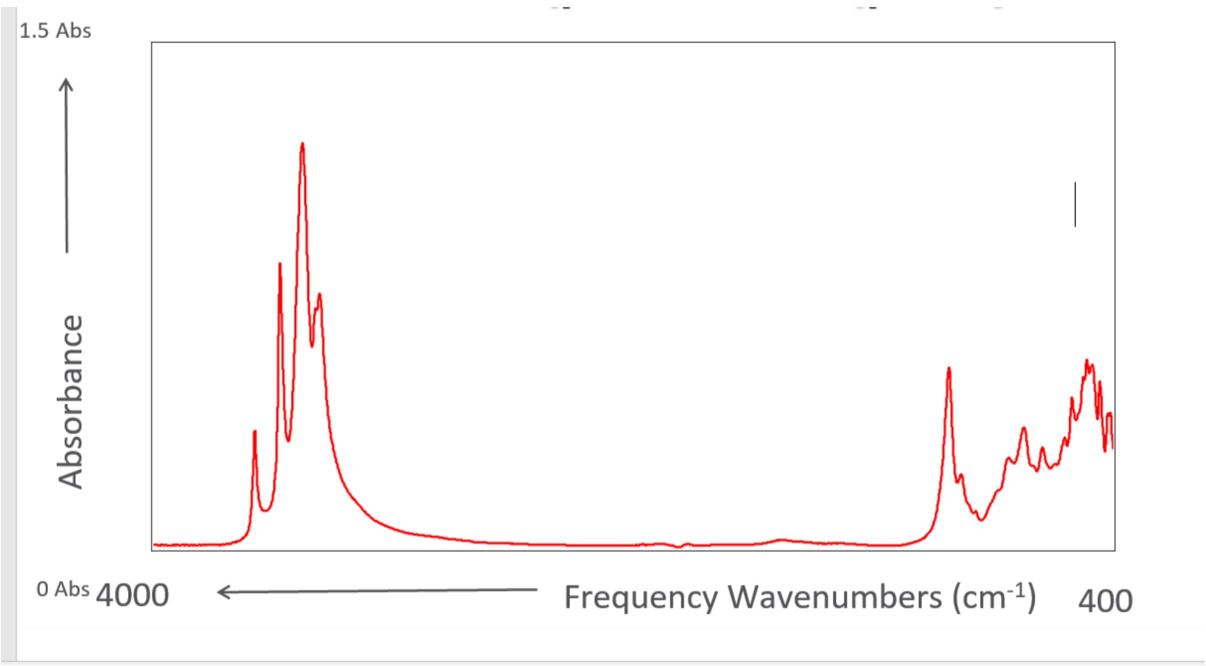

Figure 3.8. FTIR Infrared spectrum in the MIR region of a soil sample

MIR spectra can be divided into four regions: 1) fingerprint (O–Si–O stretching and bending) from 1500 to 600 cm−1; 2) double bond (C=O, C=C, and C=N) from 2000 to 1500 cm^{-1}; 3) triple bond (C≡C, C≡N) from 2500 to 2000 cm^{-1}; and 4) X–H stretching (O–H stretching) from 4000 to 2500 cm^{-1}. Clay minerals have a significant influence on soil reflectance (Sila, 2016). The bands assigned to OH and Si-O groups makes the distinction between clay minerals possible (see Janik et al., 2007).

The MIR spectroscopy allows the characterization of complex soil components, and thus has frequently been applied to investigate soil properties and soil organic matter (Viscarra Rossel *et al.*, 2006).Statistical Multivariate calibration (chemometrics) techniques of soil MIR spectra data

The purpose of calibration model is to substitute the conventional soil measurement procedures with alternative that is comparatively cheaper, faster, easily accessible, yet substantially accurate. Chemometric methods based on multivariate mathematical-statistical techniques are suitable to quantify the statistical relationship between independent variables (eg. spectral reflectance of soil samples) and dependent varaibales (eg. reference soil parameters). The development of quantitative models for prediction of soil properties can collectively be referred to as multivariate calibration (MC). Common MC methods include linear methods (e.g. multiple linear regressions (MLR)), partial least squares (PLS), principal component regression (PCR). Non-linear methods include random forest regression (RF), non-linear support vector machines (SVM), artificial neural networks (ANN) (Mutuma, 2017).

In this study Partial Least Squares Regression (PLSR) with leave-one-out cross validation was used to calibrate the MIR spectral data with the reference laboratory soil data. Data was split into calibration and validation set. Due to a small number of samples and based on the experience from previous studies (e.g. Mutuma et al. 2017), preclassification of data was not considered. During analysis, outliers were detected and eliminated to enhance the model's predictive abilities (Kawamura et al., 2017). The PLSR algorithm selects successive orthongonal factors that maximize the covariance between the predictor or independent variables (MIR spectra) and response or dependent variables (laboratory soil parameters). The PLSR is one of the most widely used chemometric methods, which is the most suitable when the number of variables exceed the number of samples, and there is a high collinearity between the variables.

3.4 Methods of Data Analysis

To achieve the stated objectives, appropriate data were subjected to various analysis techniques. This subsection describes the different techniques applied onto respective research questions.

Data from questionnaires and laboratory soil measurements were entered into separate Excel sheets and later imported to SPSS and R environment for analysis. A third Excel file, merging social and soil data was prepared and subjected to similar treatment.

Prior to analysis, questionnaire data was screened for completeness, and consistency checked based on the control questions. Raw data was classified into defined usable categories, followed by coding (Kothari, 2004). New variables were generated to facilitate the realization of the study objectives.

Qualitative data from interviews were analysed using thematic analysis. This is an independent descriptive method generally described as a technique for identifying, analysing and reporting patterns (or themes) contained within the dataset. Thematic analysis (TA) presents a theoretically flexible technique of analysing qualitative data (Braun & Clarke, 2006) and aid in validation of responses from questionnaires. Information generated from interviews was used to complement questionnaire data and enhance interpretation of statistical analysis results.

3.4.1 Characterization and classification of soils of the study area

Descriptive statistics for soil data were generated in SPSS. The means were generated for the numerical soil properties (see section 3.3.3) for the measured soil attributes). Categorical data (such as texture and Munsell colour), were summarized using "frequency distributions" analysis.

Analysis of variance (ANOVA) in SPSS was used to determine the relationship between soil properties and the three sampling depth intervals, namely 0-20 cm, 20-50 cm and 50-100 cm.

Soil classification of the visited sites was conducted based on World Reference Base of soil resources (WRB) 2014 soil classification guideline (IUSS Working Group WRB, 2015). The WRB is based on a diagnostic approach which is defined in terms of diagnostic horizons, diagnostic properties and materials, that are measurable to the greatest extent possible field observable features (IUSS Working Group WRB, 2015). The WRB comprises two levels: 1) at the first and highest level, having 32 RSGs, soils are defined by the classification key based on the presence (or absence) of a combination of diagnostics; 2) at the second level, a set of qualifiers (principal and supplementary) are added to the RSG name to provide more information for a robust classification (IUSS Working Group WRB, 2015).

To determine the relationship between soil properties and RSGS, ANOVA was conducted using the R statistical environment (Roudier & Hedley; R Core Team, 2013).

Principal component analysis (PCA) and multiple correspondence analysis (MCA) were performed for soil properties (numeric) and RSGs (categorical), respectively, to compare variability of soil properties. These procedures were implemented using a mixed PCA procedure that integrates numeric and categorical variables (Chavent et al., 2015). The soil diagnostic properties were described using the approach in terms of their physical and chemical characteristics. Variables used in the model are presented (Table 3.1)

Table 3.1. Selected soil variables for PCA and MCA analysis

Variable name	Variable descriptions	Measurement/units	Scale
		Soil properties	
BS	Base saturation	%	Numeric
CEC	Cation exchange capacity	cmol/kg	Numeric
OC	Organic carbon	%	Numeric
Ca	Exchangeable Calcium	cmol/kg	Numeric
Na	Exchangeable Sodium	cmol/kg	Numeric
K	Exchangeable Potassium	cmol/kg	Numeric
Mg	Exchangeable Mg	cmol/kg	Numeric
P	Available phosphorus	mg/kg	Numeric
Clay	Clay	%	Numeric
Sand	Sand	%	Numeric
Silt	Silt	%	Numeric
		Reference soil groups	
Nitisol	Nitisol	Yes=1, No=0	Categorical

Acrisol	Acrisol	Yes=1, No=0	Categorical
Andosol	Andosol	Yes=1, No=0	Categorical
Cambisol	Cambisol	Yes=1, No=0	Categorical
Gleysol	Gleysol	Yes=1, No=0	Categorical
Umbrisol	Umbrisol	Yes=1, No=0	Categorical
Leptosol	Leptosol	Yes=1, No=0	Categorical
Plinthosol	Plinthosol	Yes=1, No=0	Categorical

3.4.2 Farming systems, soil fertility management practices (SFMP), and determinants of SFMP adoption.

Descriptive statistics using frequency distributions (for categorical variables) and means (continuous variables) were generated in IBM SPSS to answer the research questions relating to: 1) Socio-economic and demographic characteristics of farm households; 2) Characteristics of farming systems; and 3) the SFMP used by farming households.

Prior to empirial analyses, clusters were generated using Ward's method of hierarchical clustering in SPSS to identify combination patterns of soil SFMP. Farmers adopt only a subset of technologies and not the entire package regardless of the attractiveness of the package (Mponela et al., 2016). Variables selected for clustering of SFMP are shown in Table 3.2.

Ward's method of hierarchical clustering was used to separate soil fertility management practices into classes (Cornish, 2007). Technology clustering is a product of maximum variance for SFMP usage across farming households (IBM, 2013). The closest (dissimilar) pairs of clusters are agglomerated by Ward's clustering. The height of the dendrogram node represents the numerical equivalences of agglomeration values. The node heights also indicate whether the clusters are genuinely distantly related based on ultrametric distances (Mponela et al., 2016). The node's height within the plot is proportional to the value of the intergroup dissimilarity between its 2 daughters. All clusters exhibiting fewer similar observations are plotted on the top nodes at lower height (Murtagh & Legendre, 2014).

Table 3.2. Variable selection for cluster analysis for soil fertility management practices

Variables	Variable description	Measurement/units
Slash_no_burn	Slash but no burn of residue	0=No, 1=Yes
Resiburn	Burning of plant residues	0=No, 1=Yes
Residue_application	Incorporation of crop residues	0=No, 1=Yes
Agroforestry	Agroforestry	0=No, 1=Yes
Manure	Manure application	0=No, 1=Yes
Minimum_tillage	Minimum tillage practiced	0=No, 1=Yes

Fertilizer	Fertilizer application	0=No, 1=Yes
Fallowing	Fallowing practiced	0=No, 1=Yes

Fisher's exact test (for categorical variables) and Welch's t-test (for continuous variables) were used for econometric analyses, to answer a research question related to how farm household socio-economic and demographic characteristics correlate with the use of SFMP. Variables used in the models are described (Table 3.3)

Table 3.3. Description of independent and dependent variables used in Fisher's and Welch's model

Variables	**Definition**	**Measurement/unit**
	Independent variables	
Gender	Gender of the household head	0=female, 1=male
Age	Age of household head	1=young (less than 40), 2=old (above 40 years)
Education	Household head education level	1= below high school, 2=above high school
Farming as primary occupation	Farming as primary occupation	0=no, 1=yes
Farming experience	Years in farming	1=below 20, 2=above 20
Contact with extension	Contact with extension in the last 5 years	0=no, 1= yes
Access to soil information	Access to training on soil management	0=no, 1= yes
Access to Soil analysis	Whether soil analysis has even been undertaken on household farm	0=no, 1= yes
Credit information	Farmer has ever received training on credit	0=no, 1= yes
Crop information	Farmer has ever received training on crop husbandry	0=no, 1= yes
Agribusiness information	Farmer has ever received training on agribusiness.	0=no, 1= yes
County	Farm location	1=Meru, 2=Tharaka Nithi
Livestock	Livstock ownership	0=no, 1= yes
Family size	Number of people in the family	Count
Farm size	Total size of landholding cultivated by household	Acres
Household income	Annual household income (on-farm and off-farm)	Ksh
Work force	Number of household members actively involved in farming	Count
*Tropical livestock units (TLU)	Aggregated livestock assets	standardized value
	Dependent variables	
Slash-no-burn	Practice slash-and-no-burn	0=no, 1= yes
Residue burn	practice residue burn	0=no, 1= yes
Residue application	Incorporates crop residues	0=no, 1= yes
Agroforestry	practice agroforestry	0=no, 1= yes
Manure	apply manure	0=no, 1= yes
Inorganic fertilizer	apply inorganic fertilizer	0=no, 1= yes
Minimum tillage	practice minimum tillage	0=no, 1= yes
Fallowing	practice fallowing	0=no, 1= yes

**The TLU conversion factors used are as follows: ox = 1.10, cow =1.0, heifer =0.50, bull=0.6, calves = 0.2, sheep and goats = 0.10, pigs = 0.20 and poultry = 0.0 1* (Storck et al., 1991)

Manure and mineral fertilizer

The adoption of the most commonly used fertility practices, namely manure and inorganic fertilizer, was explored further, using Fisher's and Welch's t-tests. Fertilizer and manure application regimes were included in the models as the dependent variables. They include questions on whether the farmer: 1) uses fertilizer, 2) uses manure, 3) applies fertilizer only during planting, 4) applies fertilizer only during top dressing 5) applies fertilizers during both planting and top dressing and 6) uses fertilizer every planting season.

3.4.3 Local indicators of soil fertility, and comparison of farmers' and scientific soil fertility measurements.

3.4.3.1 Description of farmers' soil fertility indicators

Descriptive statistics of soil fertility indicators used by farmers to classify fertile and infertile soils, were generated in SPSS. Frequencies and percentages of farmers' perception of fertile and infertile soils based on the 9 parameters provided in the questionnaire, namely soil colour, soil earthworms, indicator weeds, topography, water holding capacity, soil workability (tilth), crop yields, crop growth and leaf colour, were determined. The comparison in soil fertility measures between high and low fertile plots was undertaken using ANOVA.

Farmers rated the importance of each indicator in evaluating soil fertility using a 5-point Likert scale (1=not important to 5= very important). Means for importance ratings were analysed using descriptive techniques in SPSS and bar charts were generated. Similarly, based on soil fertility descriptions in relation to the various indicators, farmers rated the quality of their fields in terms of each indicator using a 5-point Likert scale (1=poor to 5=excellent).

The subsequent subsections describe how soil quality thresholds (both scientific and farmer-based) were determined.

3.4.3.2 Farmer-descriptive soil quality index (SQI)

After describing fertile and infertile soils, farmers evaluated fertility of their fields in respect to each of the indicators by giving a score of 1-5 (poor to excellent soil quality). The farmer descriptive SQI was generated by averaging the sums of the 9 indicator scores for each farm, resulting into an aggregated farmer criterion for soil quality assessment. Based on the average fertility score, the soils were classified as either infertile (<3.5) or fertile (>3.5).

3.4.3.3 Indicator selection and determination of scientific soil quality indices (SQIs)

Two methods were used to develop scientific soil quality indices based on measured soil properties, including a simple additive procedure (additive SQI) and mathematically developed soil quality index using factor analysis (FA-SQI). The simple additive SQI was estimated following procedures outlined by Amacher et al. (2007) and Vlek et al. (2010). In this method, soil parameters were given threshold values based on the literature review. The threshold levels, interpretations, and associated dimensionless soil quality index score values are listed in (Table 3.4). The individual index values for the physical, chemical and biological soil properties were summed to give the additive SQI. The parameters selected for the SQI scale included sand (coarse fraction) (physical), soil pH (chemical), soil organic carbon (biological), CEC (%) (Chemical), potassium (chemical), magnesium (chemical), calcium (chemical), and available P (chemical).

The rationale for the scoring method that was used for each soil indicator is explained as follows. Soils with a coarse fragment content of > 50 percent have a greater probability of adverse effects from infiltration rates that are too high, water storage capacity that is too low, more difficult root penetration, and greater difficulty in seed germination and seedling growth. High coarse fragment contents have been shown to limit soil productivity (Rodrigue & Burger, 2004). Although many plant species are adapted to acidic or alkaline soils, vegetation diversity tends to decline at strongly acid (pH < 4) or strongly alkaline (pH > 8.5) pH levels. It also affects the availability of many plant nutrients (Miller & Gardiner, 2001). Organic matter is a key component of soils because of its influence on soil physical and chemical properties and soil biota (Fisher, 1995). Soils with total organic carbon (TOC) of less than 1 percent, are at a greater risk of decline from soil erosion and/or other disturbances that accelerate organic matter loss (NRCS, 2003). Plants growing in soils with very low levels of exchangeable K and Mg (< 100 and 50 mg/kg, respectively) have a greater probability of exhibiting deficiency symptoms than plants growing in soils with higher levels of these elements. High values of CEC indicate that soil has a better capacity to hold cations. Low CEC soils can hold less amounts of soil nutrients, and are usually at risk of leaching mobile nutrient anions. Table 3.4 shows the indicators selected for the determination of the soil quality index. The presented parameters, which constitute only a sub-set of the properties proposed by Armacher et al. (2007) are the variables that were used in the additive SQI derivation and the most critical in evaluating soil quality dimensions.

Table 3.4. Indicator scoring for calculation of the additive soil quality index

Parameter	Range		Score	Interpretation
Sand (coarse fraction %)	0	50	1	Adverse effects unlikely
	50	100	0	Possible adverse effects
PH	3.01	4	0	Strongly acid
	4.01	6	1	Moderately acid to neutral
	>6		0	Basic soils
TOC (%)	0	1	0	Low – possible loss of organic C
	1	5	1	Moderate – adequate levels
	>5		2	High – excellent buildup of organic C
CEC (%)	0	10	0	Low CEC- low nutrient and water holding capacity
	10	15	1	Moderate-adequate levels
	>15		2	High CEC: excellent nutrient holding capacity
K (mg/kg)	0	100	0	Low – possible deficiencies
	100	500	1	Moderate – adequate levels
	>500		2	High – excellent reserve
Exch. Mg (mg/kg)	0	50	0	Low – possible deficiencies
	50	500	1	Moderate – adequate levels
	>50		2	High – excellent reserve
Exch. Ca (mg/kg)	0	10	0	Low – possible deficiencies
	10	1000	1	Moderate – adequate levels
	>1000		2	High – excellent reserve
Available P (mg/kg)	0	15	0	Low – possible deficiencies
	15	30	1	Moderate – adequate levels
	>30		2	High – excellent reserve
Available N (mg/kg)	0	75	0	Low available N
	75	125	1	Moderate available N
	>125		2	High available N
Maximal additive SQI			16	

Adapted from Amacher et al. (2007)

In the factor analysis-derived soil quality indicator score factor analysis (FA) was used to create a minimum data set to reduce the indicator load and minimize data redundancy, using SPSS version 25 procedures. Factors were derived using Varimax rotation procedure and factor scores saved in the original dataset for each farm. Each of the extracted factors explained a given amount of variance in the model. The % variance for each factor was divided by the cumulative variance to derive a weight for each factor (PC), which was multiplied by the factor scores for each sampled farm (Andrews et al., 2002). The weighted multivariate soil quality indicator was derived as follows as presented in Equation (7)

$$FA\text{-}SQI = w1 * Component\ 1\ score + w2 * Component\ 2\ score + w3 * Component\ 3\ score \quad (7)$$

Where w1-w3 are the factor weights

3.4.3.4 Measuring relations between the different soil quality indices

The two scientific SQIs (additive SQI and FA- SQI) were regressed against farmer-descriptive SQI. To relate the farmer-descriptive SQI and the scientific indicators, two regression models using the lm procedure (R) were used. First, the farmer-descriptive SQI was regressed against the additive SQI. Finally, the farmer-descriptive SQI was regressed against the FA-SQI, and linear model facets for high and low fertility plots were produced using sub-setting procedures in R.

3.4.4 The influence of farmers' socio-economic and management practices on soil quality.

Farming systems in the tropics are diverse, representing biophysical, institutional, social and economic drivers which differ between contexts, resulting in different responses of farmers and communities between and within areas (Rapsomanikis, 2015; Tittonell et al., 2005). Over time, these differences in drivers and in farm features lead to temporal and spatial variability between and within farming systems. The existing farming systems variability is challenging to fully comprehend, leading to partial representation of reality. Various tools and methods (e.g. farm typologies) have been developed to understand and deal with farming systems diversity.

3.4.4.1 Principal components analysis

Multivariate analysis procedures including Categorical Principal Analysis (CATPCA) and Factor Analysis (FA) were used to determine discriminant variables for cluster analysis (CA) (Giller et al., 2011). These kind of methods are also referred to as 'dimension reduction' or 'data-reduction' techniques (Pacini et al., 2013) because they have the advantage of capturing the complexity of farming systems through taking into account numerous farm dimensions and highlighting a few dimensions that are more explanatory of farm diversity (Alary et al., 2002). Analysis for principal components or factors procedures were perfomed separately for three groups of variables: Socio-ecomic, farm characteristics and soil properties (Table 3.5 and Table 3.6). PCA and CA have widely been used to classify farms (Dossa et al., 2011). The use of CATPCA technique was preferred over the standard PCA, since it can handle variables of multiple measurement levels (nominal, ordinal, and numerical). In this case, it was used in the analysis of socio-ecomic variables and farm characteristics, which were largely categorical.

Table 3.5. Socio-economic and farm variables used in CATPCA model

Variables	Definition	Measurement/unit
	Household socio-economic characteristics	
Gender	Gender of the household head	0=female, 1=male

Variables	Definition	Measurement/unit
Household socio-economic characteristics		
Age	Age of household head	1=young (less than 40), 2=old (above 40 years)
Education	Household head education level	1= below high school, 2=above high school
Farming Occup	Farming as primary occupation	0=no, 1=yes
Experience	Years in farming	1=below 20, 2=above 20
Extension Contact	Contact with extension in the last 5 years	0=no, 1= yes
Soil info	Access to training on soil management	0=no, 1= yes
Soil testing	soil analysis has even been undertaken on farm	0=no, 1= yes
Credit information	Farmer has ever received training on credit	0=no, 1= yes
Crop information	Farmer has ever received training on crop husbandry	0=no, 1= yes
Agribusiness info	Farmer has ever received training on agribusiness.	0=no, 1= yes
Livestock	Livestock ownership	0=no, 1= yes
Family size	Number of people in the family	Count
Farm size	Total size of landholding cultivated by household	Acres
Household income	Annual household income (on-farm and off-farm)	Ksh
Work force	Number of household members actively involved in farming	Count
TLU*	Aggregated livestock assets	standardized value
Cropping practices and soil fertility management		
PCrop	Pure crop stands practiced	0=no, 1=yes
Mixed	Mixed cropping practiced	0=no, 1=yes
Agrof	Agroforestry practiced	0=no, 1=yes
IntCrop	Intercropping practiced	0=no, 1=yes
Residue	Farm residues applied	0=no, 1=yes
Manure	Manure applied	0=no, 1=yes
Mintill	Minimum tillage practiced	0=no, 1=yes
Fallow	Fallowing practiced	0=no, 1=yes
Incorp	Incorporation practiced	0=no, 1=yes
Burn	Burning residues practiced	0=no, 1=yes
Compost	Compost manure applied	0=no, 1=yes
Fodder	Farm organic materials used as fodder	0=no, 1=yes
Fuel	Farm organic materials used as fuel	0=no, 1=yes
Fert. Plant rate	Amount of fertilizer used during planting	Kg/ ha
Fert.Topdress rate	Amount of fertilizer used during for top dressing	Kg/ha

Table 3.6. Soil properties variable used in Factor analysis

Variables	Definition	Measurement/unit
Soil quality characteristics		
Ca	Exchangeable Calcium	cmol/kg
Mg	Exchangeable Magnesium	cmol/kg
Na	Exchangeable Sodium	cmol/kg
K	Exchangeable Potassium	cmol/kg
PH	PH water	
OC	Total organic carbon	%

Variables	Definition	Measurement/unit
	Soil quality characteristics	
CEC	Soil CEC	%
P	Soil available P	Mg/kg
N	Soil available N	Mg/kg
Clay	Clay content	%
Sand	Sand content	%
Silt	Silt content	%
BS	Base saturation	%
AL-K2O	Extractable potassium	Mg/kg
Moisture	water holding capacity	%

The farm typology was conducted by PCA followed by cluster analyses of the PCA results. PCA analysis is useful in predicting a priori the number of homogenous groups in the data sets (Dossa et al., 2011; Tittonell et al., 2010). Both the eigenvalue rule (>1) and Cronbach's alpha threshold were applied in determing the optimal number of components.

Factors for soil characteristics were extracted using PCA and Varimax roration with Kaiser Normalization. The eigenvalue threshold (>1), the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy (>0.5) and Bartlett's test of sphericity significance (<0.00001) were applied (Hair et al., 2010).

The data was standardised for analysis automatically using the PCA procedure prior to analysis. Outliers in the data were examined and revised accordingly. Loadings that were greater or equal to 0.4 were considered for interpretation purposes (Samuels, 2017).

3.4.4.2 Clustering and Farm typologies

Soil variables with the highest discriminating power in each component of FA solution were submitted to Two-step CA. The Two-step CA technique is recommended for datasets consisting of both continuous and categorical variables (Dossa et al., 2011). Numeric variables are standardized by default. The log-likelihood distance method of distance measure was applied (Dossa et al., 2011). Generally, the number of clusters is automatically determined based on Bayesian Information Criterion (BIC). However, where the resulting clusters fail to present a true picture of the field observations, the analysis is repeated with pre-determined number of clusters until a meaningful classification is achieved (Goswami et al., 2014). The silhouette measure of cluster cohesion and separation value was used to validate the cluster solution. A silhouette is a graphical aid to the interpretation and validation of CA that indicates a measure of how well a subject is classified in relation to membership allocation (Jain & Koronios, 2008).

After the clustering procedure, the non-hierarchical algorithm re-assigned farms to the generated clusters. The differences in characteristics between the clusters were explored using Fisher's Exact Test (FET) and one-way ANOVA for categorical and continuous variables, respectively. FET is highly recommended as it gives an exact accurate and unbiased p-value for small sample sizes or when the expected numbers are small (Kuria et al., 2018).

4 RESULTS AND DISCUSSION

This section is organized based on objectives. Results related to a given objective are first presented and then followed by discussion.

4.1 Results

4.1.1 Soil Characterization of Sampled Farms

The first objective of this study was to determine soil characteristics and spatially define/visualize soil properties of the study site. Soil properties were determined using various laboratory protocols explained earlier in section 3.4.

4.1.1.1 Accuracy of soil property predictions

The accuracy of soil property prediction was characterized by the R^2 (determination coefficient) and RMSE (root mean squared error) of the model. High R^2 and low RMSE value means better prediction accuracy. Since organic carbon content and pH were determined for all the samples the prediction was performed for exchangeable bases (Ca, Mg, Na, K), sand, silt, clac content, cation exchange capacity (CEC), AL-K_2O, AL-P_2O_5, and N. Base saturation was calculated from CEC and the exchangeable bases. The R^2 and RMSE vales are indicated in Table 4.1. The poor prediction of exchangeable bases is due to low concentration thus difficult to detect.

Table 4.1. R^2 and RMSE results of soil properties predictions

Soil property	R^2	RMSE
Exch. Ca	0.18	0.23
Exch. Mg	0.22	0.21
Exch. Na	0.08	0.02
Exch. K	0.09	0.45
Sand	0.78	5.2
Silt	0.77	6.4
Clay	0.89	3.5
CEC	0.76	2.1
AL-K_2O	0.54	72.3
AL-P_2O5	0.57	2.3
N	0.45	3.98

4.1.1.2 Results of descriptive statistics of soil properties

Soil attributes of the visited sites are presented (Table 4.2).

Table 4.2. Overall descriptive statistics of laboratory measurements of soil properties and across the three depths

Depth	**20**			**50**			**100**			**Total**		
Variable	Mean	N	Std. Dev	Mean	N	Std. Dev	Mean	N	Std. Dev	Mean	N	Std. Dev
Sand	25.48	69	7.65	22.44	66	7.02	20.61	65	5.98	22.89	200	7.19
Silt.	38.33	69	4.5	40.1	66	4.16	41.26	65	3.53	39.87	200	4.25
Clay	36.19	69	3.15	37.46	66	2.86	38.13	65	2.66	37.24	200	3
Bs	17.26	69	4.66	16.86	67	4.74	17.07	66	4.32	17.07	202	4.56
K.	0.81	68	0.1	0.81	67	0.13	0.82	64	0.12	0.81	199	0.12
Mg.	0.67	69	0.18	0.65	67	0.18	0.66	66	0.16	0.66	202	0.17
Ca	1.89	69	0.42	1.88	67	0.42	1.87	66	0.47	1.88	202	0.43
Na.	0.04	67	0.05	0.05	64	0.05	0.06	64	0.06	0.05	195	0.05
CEC.	8.47	69	1.44	8.39	67	1.82	8.39	65	1.73	8.42	201	1.66
AL-K2O	781.84	69	117.28	742.04	66	118.61	718.33	64	103.91	748.21	199	116.08
AL.P2O5.	11.32	69	7.7	13.14	67	9.33	12.77	63	9.73	12.39	199	8.92
pH.H2O.	5.49	69	0.74	5.31	68	0.98	5.4	65	0.89	5.4	202	0.88
OC.	0.97	68	0.52	1.16	67	0.86	1.1	63	0.69	1.08	198	0.71
Moisture	4.54	69	2.17	4.59	67	2.42	4.32	64	2.4	4.48	200	2.32
N (mg/Kg)	24.46	55	22.56							24.46	55	22.56

The soils in the study area had generally low pH, OC, CEC, BS and clay content. The pH level ranged from 3.9 to 7.0. SOC ranged from a low of 0.5 to 5.9%. CEC and BS ranged from 4.0 to 25 cmol/kg and 1.0 to 52%, respectively. Figure 4.1 and Figure 4.2 shows the patterns in soil properties across the sampling sites.

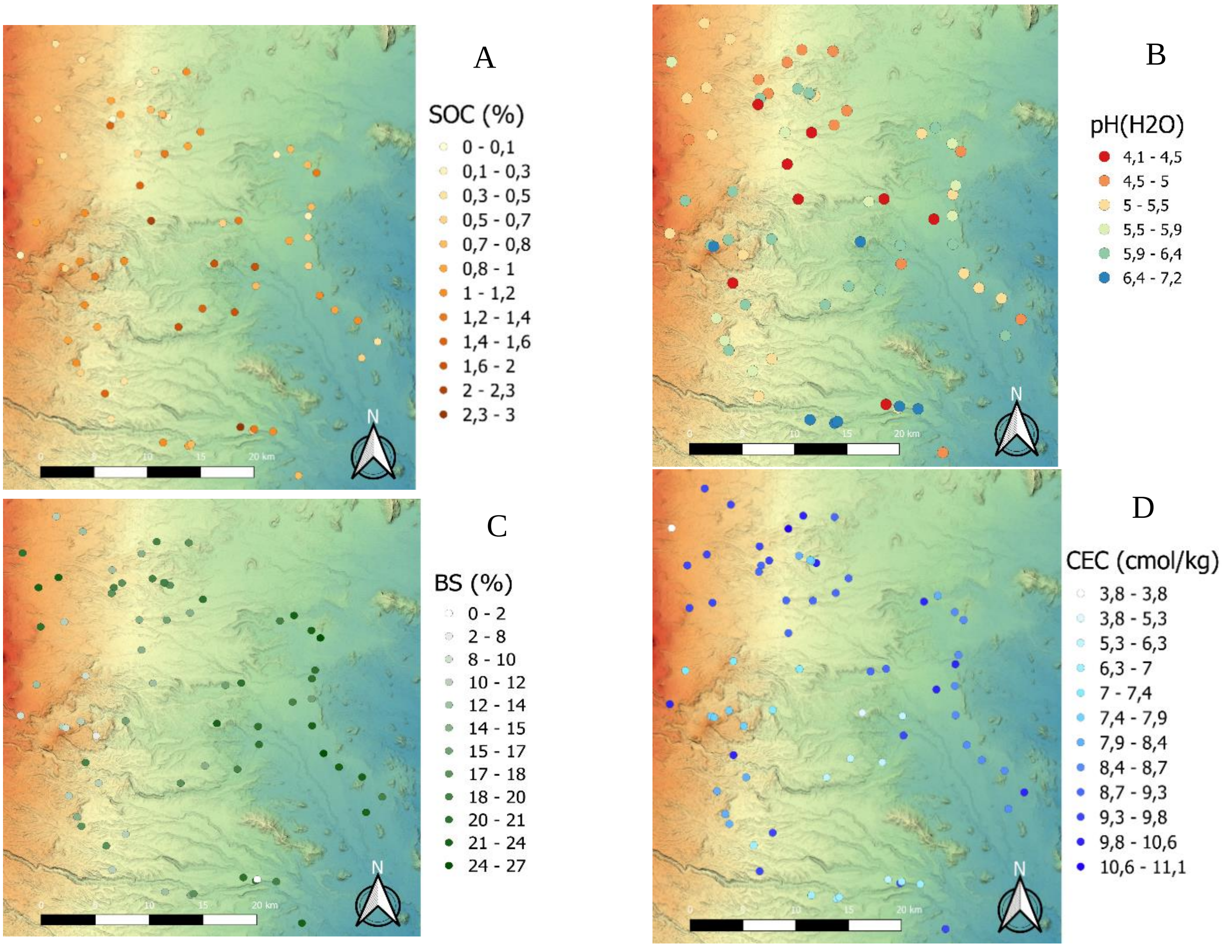

Figure 4.1. Soil property maps for selectected attributes: soil organic carbon (A), pH (B), Base saturation (C) and Cation exchange capacity (D)

Clay content was higher in uplands fields (sites near the slope of Mount Kenya) and decreased towards the east. CEC was higher in the northern parts of the survey area compared to the lowlands in the south. Base saturation was lower in the uplands and highest in the eastern part of the study area. SOC was higher in the Upper Midlands with lowland areas recording low levels. There was no clear predictable pattern in the soil mineral nutrient properties, namely extractable K and available P.

There were significant differences for the three textural proportions across the depths (Table 4.3). There was more sand in the topsoil. Silt was higher at 0-50 cm depth. Clay was higher below 50 cm depth. The overall average pH (with water) was 5.4, and was fairly homogenous across the depths. The mean OC was 1% and ranged between 0.1 and 5%. The mean Base saturation was 17% (ranging between 2% and 27%) and was homogenous across the depths.

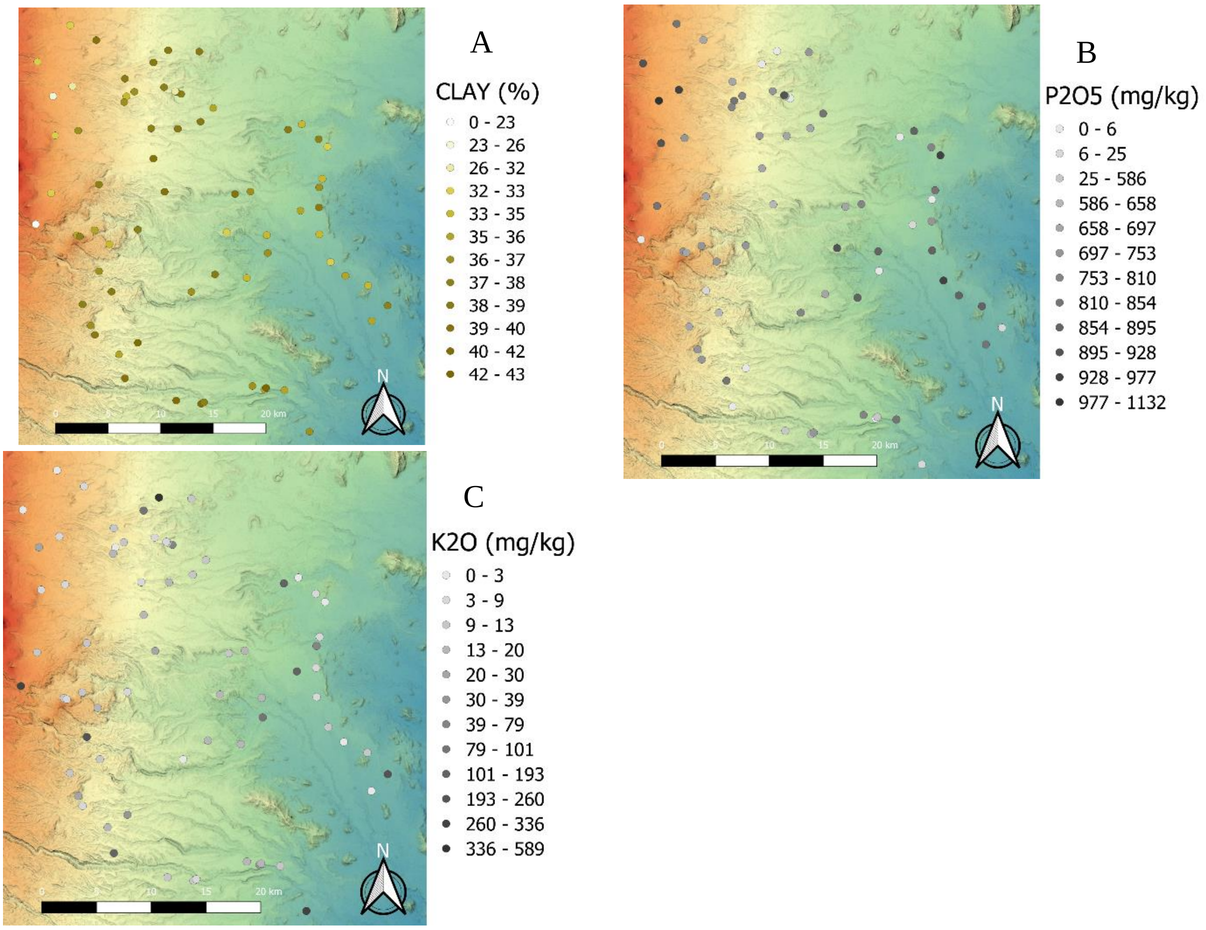

Figure 4.2. Soil property maps for selectected attributes: Clay (A), Available P (B) and extractable K

The overall mean CEC was 8.4 cmol/kg, with a low of 0.7 and a high of 13 cmol/kg without significant differences across depth. The mean for basic cations was 0.8, 0.7, 1.9 and 0.05 cmol/kg for K, Mg, Ca and Na respectively. There were no variations across depth intervals. These soils are generally acidic and highly leached, thus the exchangeable bases are almost absent. The overall mean for extractable K, available P and N were 748, 12 and 24.5 mg/kg respectively. There were high variations in K across depths with the topsoil recording higher amount. The amount of K across all the sampling depths ranged between 371 and 1132 mg/kg.

Table 4.3. Results of ANOVA showing tendencies of soil properties across the three sampling depths (0-20, 20-50, 50-100cm)

Property	**df**	**F**	**Sig.**
Sand	2	8.485	0.000***
Silt	2	8.777	0.000***
Clay	2	7.74	0.001***
BS	2	0.131	0.878
Exch. K	2	0.064	0.938
Exch. Mg	2	0.131	0.878
Exch. Ca	2	0.022	0.979
Exch. Na	2	1.651	0.194

CEC	2	0.044	0.957
AL-K2O	2	5.333	0.006**
AL.P2O5	2	0.792	0.455
pH.H2O	2	0.784	0.458
OC.	2	1.224	0.296
Moisture	2	0.243	0.785

, *, significant at 5% and 1%, respectively

4.1.1.3 Correlations of soil properties

There were noticeable significant dependencies among the soil properties (Table A 15). Available P had negative associations with CEC, silt, clay, moisture and pH, with correlation coefficients (cc) of -0.308, -0.220, -0.229 and -0.265, respectively (p-value <0.01). Properties that exhibited positive relationship with P include Exchangeable K (0.162, p<0.05), OC (0.584, p<0.01) sand (0.225, p<0.01) and extractable K (0.156, p<0.05).

Extractable K had significant negative correlation with pH (by water), silt, clay and exch. K, with cc -0.196 (p<0.01), -0.965 (p<0.01), -0.948 (p<0.01), -0.165 (p<0.05). Positive correlation was exhibited between K_2O and sand (0.958, p<0.01), BS (0.760, p<0.01), Mg (0.760, p<0.01), Ca (0.514, p<0.01) and soil moisture (0.157, p<0.05).

A strong positive correlation was exhibited between CEC and moisture content (0.956, p<0.01). Soil properties with negative correlations with CEC include exch. K (-0.948, p<0.01), Na (-0.208, p<0.01), OC (-0.735, p<0.01), and pH (-0.510, p<0.01).

Clay was strongly correlated to silt (0.966, p<0.01), sand (-0.988, p<0.01) K2O (-0.948, p<0.01), BS (-0.509, p<0.01) and Mg (-0.509, p<0.01). Other properties that exhibited significant association with clay include available N (-0.392, p<0.01), exch. K (0.157, p<0.05), Ca (-0.325, p<0.01), available P (-0.232, p<0.01), moisture (-0.156, p<0.05) and pH (0.164, p<0.05).

Available N was significantly and positively correlated with sand (0.367, p<0.01). A couple of properties exhibited a negative correlation with N and include silt (-0.350, p<0.01), BS (-0.424, p<0.01), Mg (-0.424, p<0.01), and OC (-0.279, 0.05).

Base saturation was strongly correlated with pH with KCl solution (0.904, p<0.01), sand (0.546, p<0.01), K_2O (0.760, p<0.01) and Ca (0.726, p<0.01). Properties that were negatively correlated with BS include silt (-0.546, p<0.01), clay (0.509, p<0.01), exch. K (-0.142, p<0.05), Mg (1, p<0.01) and pH with water (-0.205, p<0.01).

SOC was positively correlated with exch. K (0.478, $p<0.01$) and Na (0.146, $p<0.01$). Parameters that exhibited a negative correlation include moisture (-0.633, $p<0.01$) and pH with water (-0.194, $p<0.01$).

A strong correlation was exhibited between pH (water) and exch. K (0.760, $p<0.01$). Other properties with positive association with pH include clay and silt (0.164, $p<0.01$). Moisture and sand had a negative correlation of -0.553 ($p<0.01$) and -0.165 ($p<0.05$) respectively.

4.1.1.4 Reference soil groups of the study area

Soil classification was done following the International soil classification system for naming soils and creating legends for soils maps described in the World Reference Base for Soil Resources 2014 (IUSS Working Group WRB, 2015).

A total of eight Reference soil groups (Figure 4.3) were determined based on WRB 2014 soil classification guideline. The most common RSG was Nitisols (mostly dystric Nitisols), occuring mainly in the areas on the slopes of Mount Kenya (Figure 4.4) due to low leaching and moderate organic matter.

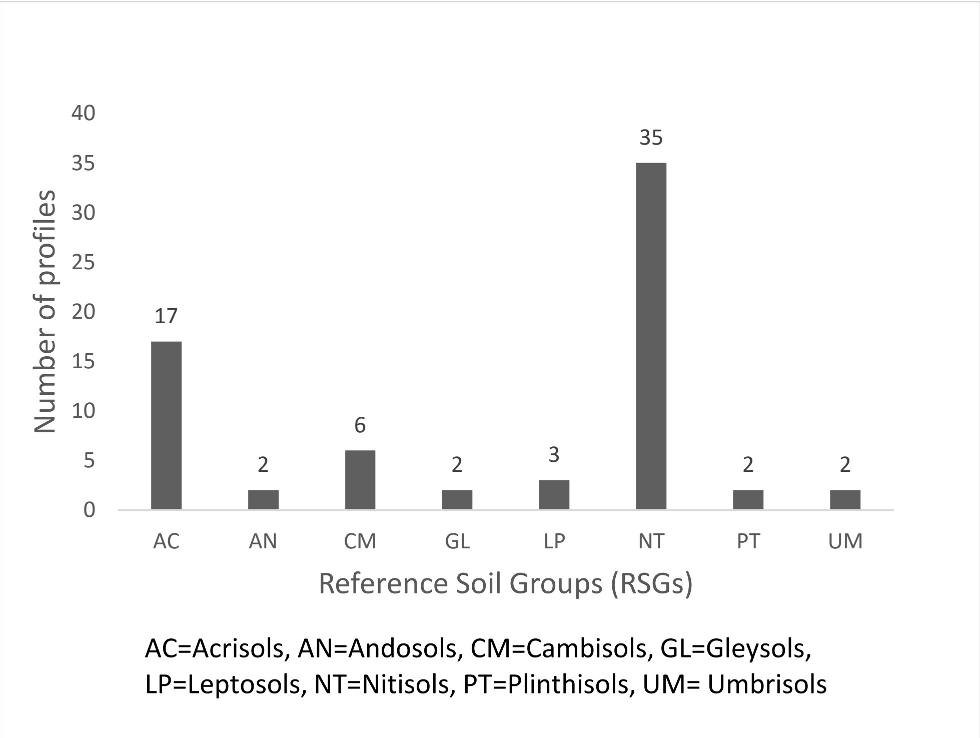

Figure 4.3. Frequencies of dentified Reference Soil Groups in the visited sites

The lower region was generally characterized by Acrisols (mostly dystric Acrisols) due to climatic conditions favourable to leaching and intense weathering. The lower areas (on flat or gently slopes) receive already weathered materials from adjacent uplands.

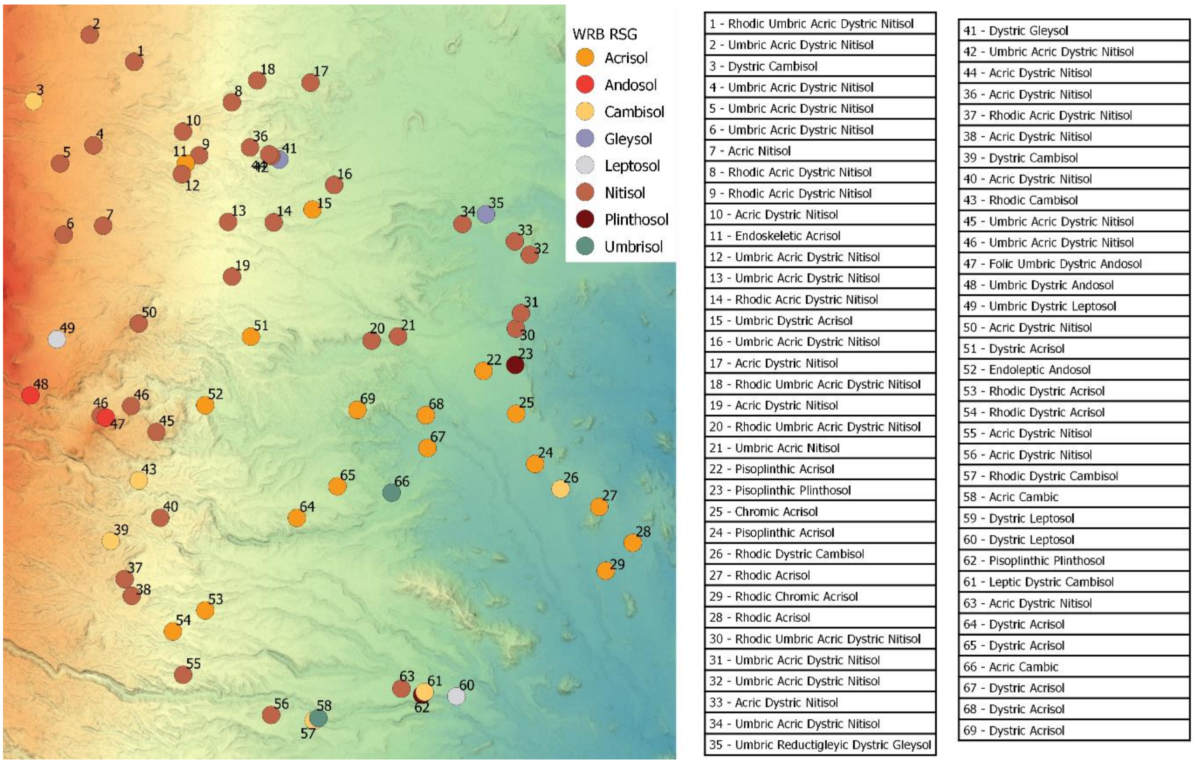

Figure 4.4. Distribution of Reference soil groups in the study sites

Detailed results of classification of the soils in the study area are presented presented in Table A 14.

4.1.1.5 Soil classification qualifiers

The wide range of qualifiers (principal and supplementary) associated with Reference soil groups in the study area (Table 4.4 and Table 4.5) in regard to classification, reveals high variability of soil types (a typical characteristic of Kenya's soil).

Principal qualifiers

Table 4.4. Principal qualifiers associated with soils of Mount Kenya East region

Principal Qualifiers	AC	AN	CM	GL	LP	NT	PT	UM	Total
Dystric	9	2	5	2	3	32			53
Acric						34		2	36
Umbric	1	2		1		17	1		22
Rhodic	4		3			8			15
Pisoplinthic	2						2		4
Cambic								2	2
Leptic	1		1						2
Skeletic	1					1			2

Gleyic	1			1					2
Folic		1							1
Chromic	1								1
TOTAL	**20**	**5**	**9**	**4**	**3**	**92**	**3**	**4**	140

Dystric and Acric were the most common principal qualifiers and were dominant in the classification of Nitisols.

Supplementary Qualifiers

Aric and Colluvic were the major supplementary qualifiers and were common in characterizing Nitisols. Cutanic and humic were dominant in the classification of Acrisols (Table 4.5).

Table 4.5. Supplementary qualifiers used in the classification of soils in Meru and Tharaka Nithi

Supplementary Qualifiers	**AC**	**AN**	**CM**	**GL**	**LP**	**NT**	**PT**	**UM**	**Total**
Acric	5	2	5	1		33	1	2	49
Colluvic	5	2	5	1		33	1	2	49
Ochric	5		4	1		8			18
Cutanic	11								11
Humic	11								11
Andic						4			4
Rhodic								2	2
Gleyic							1		1
Fluvic					1				1
Escalic			1						1
Acric				1					1
Clayic					1				1
TOTAL	**37**	**4**	**15**	**4**	**2**	**78**	**3**	**6**	149

4.1.1.6 Diagnostic Horizons and Properties

Nitic, Argic and Umbric were the most prevalent diagnostic horizons (Table 4.6) and were largely associated with Nitisols and Acrisols.

Table 4.6. Frequencies of Diagnostic horizons and properties associated with RSGs of Mount Kenya East region

Diagnostic properties	**NT**	**AC**	**CM**	**GL**	**UM**	**AN**	**LP**	**PT**	**Total**
Argic	35	17	0	1	2	0	0	0	55
Nitic	35			1					36
Umbric	19	1		1	2	1	1		25
Colluvic mat	3	1	2		2				8
Cambic			6						6
Andic	4					1			5

Pisoplinthic		2						2	3
Gleyic prop	1			1					2
Reducing cond	1			1					2
Continuous rock							2		2
Colluvic							1		1
Continuous rock			1						1
Fluvic							1		1
Protovertic	1								1
Umbric Andic						1			1
Folic						1			1
Gleyic prop				1					1
Total	99	21	9	6	6	4	5	2	152

4.1.1.7 Mean soil Properties by RSGs

Variations of soil attributes across across RSGs are presented (Figure 4.5 and Figure 4.6). The soil CEC varied by RSG groups, significantly (Figure 4.5). Nitisols recorded the highest soil CEC, which was not different from Andosols and Leptosols. The least CEC was in Umbrisols, which was different from other groups except Leptosols. The SOC was highest in Umbrisols, while soil pH was highest in Cambisols, and least in Andosols. The Base saturation was highest in Gleysols, while clay content was highest in the Cambisols. The Andosols recorded the highest sand content, while Cambisols showed the highest silt contents.

The available N was highest in Andosols, but there were no significant differences in the means. Soil Ca, K, P, and magnesium showed significant differences in means by RSG soil groups (Figure 4.6). The highest means were reported in Gleysols for Calcium while Acrisols had the least Ca concentration. Sodium concentration did not vary by RSG groups while Potassium was highest in Gleysols compared to other soils. In relation to soil phosphorous, the highest values were observed in Andosols and Leptosols while Magnesium was highest in Gleysols and Acrisols.

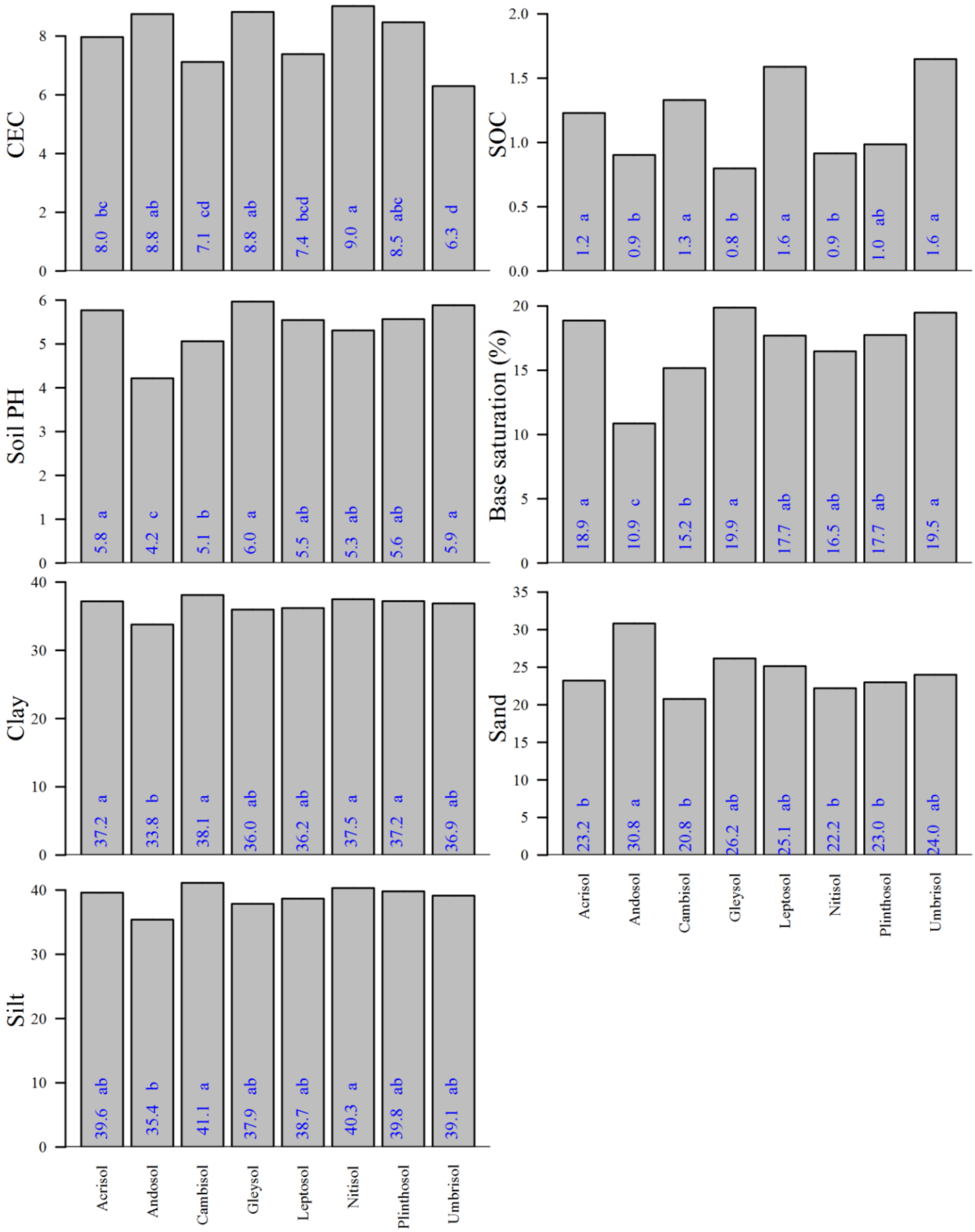

Figure 4.5. Tendencies of CEC, pH, SOC, BS, and texture proportions across the RSGs

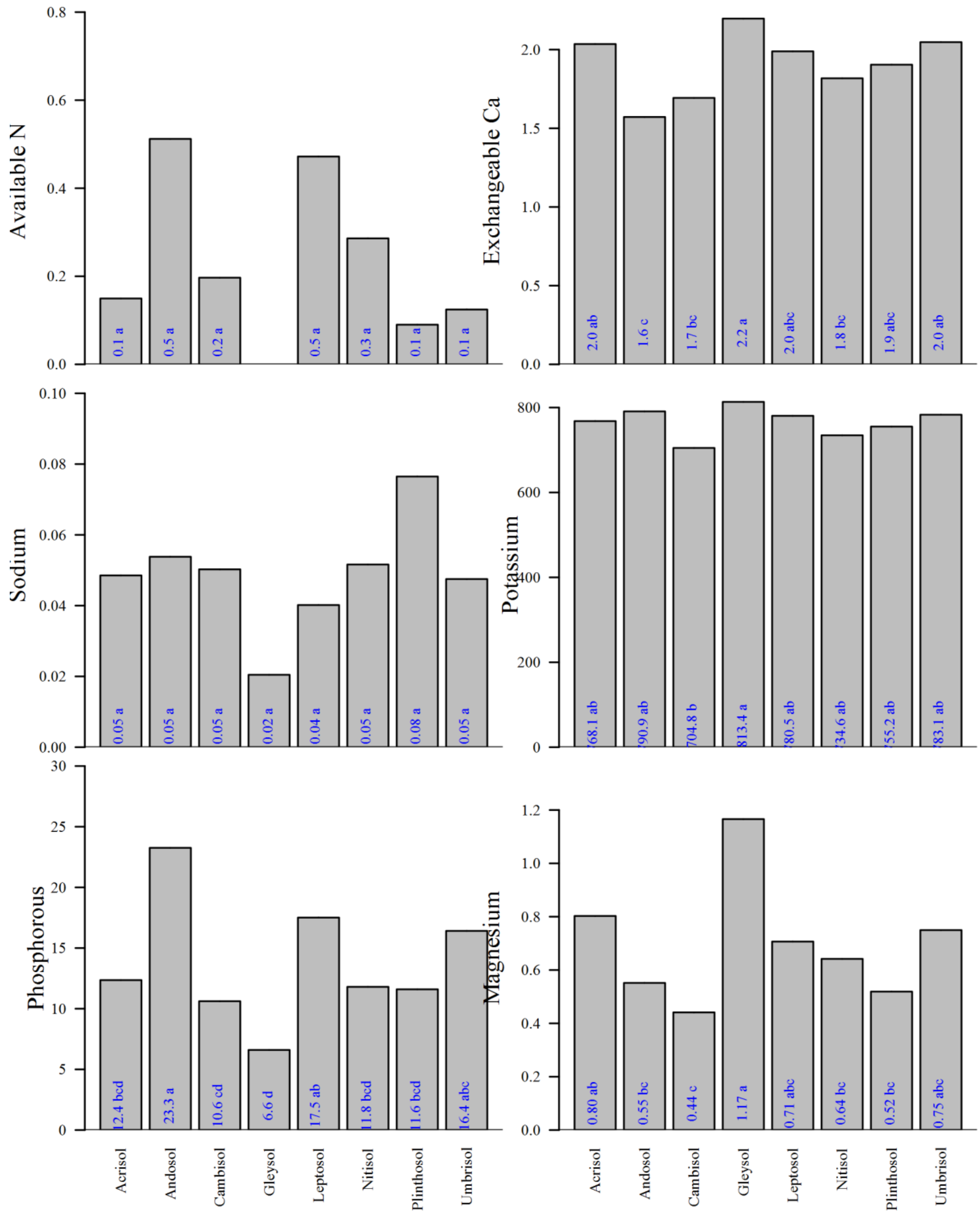

Figure 4.6. Tendencies of Exchangeable bases and mineral nutrients across the RSGs

4.1.1.8 PCA biplot of soil properties, MCA and RSG

The PCA for soil properties (numeric) and MCA (categorical) was implemented using a mixed PCA procedure that integrates numeric and categorical variables (Figure 4.7). The soil diagnostic properties were described using the approach in terms of their physical and chemical characteristics. The Andosols, Umbrisols, and Leptosols were closely associated in terms of their chemical characteristics including SOC, P, and Na contents, indicating that they had almost similar characteristics in these parameters. Nitisols were a distinct soil group with high silt and clay contents.

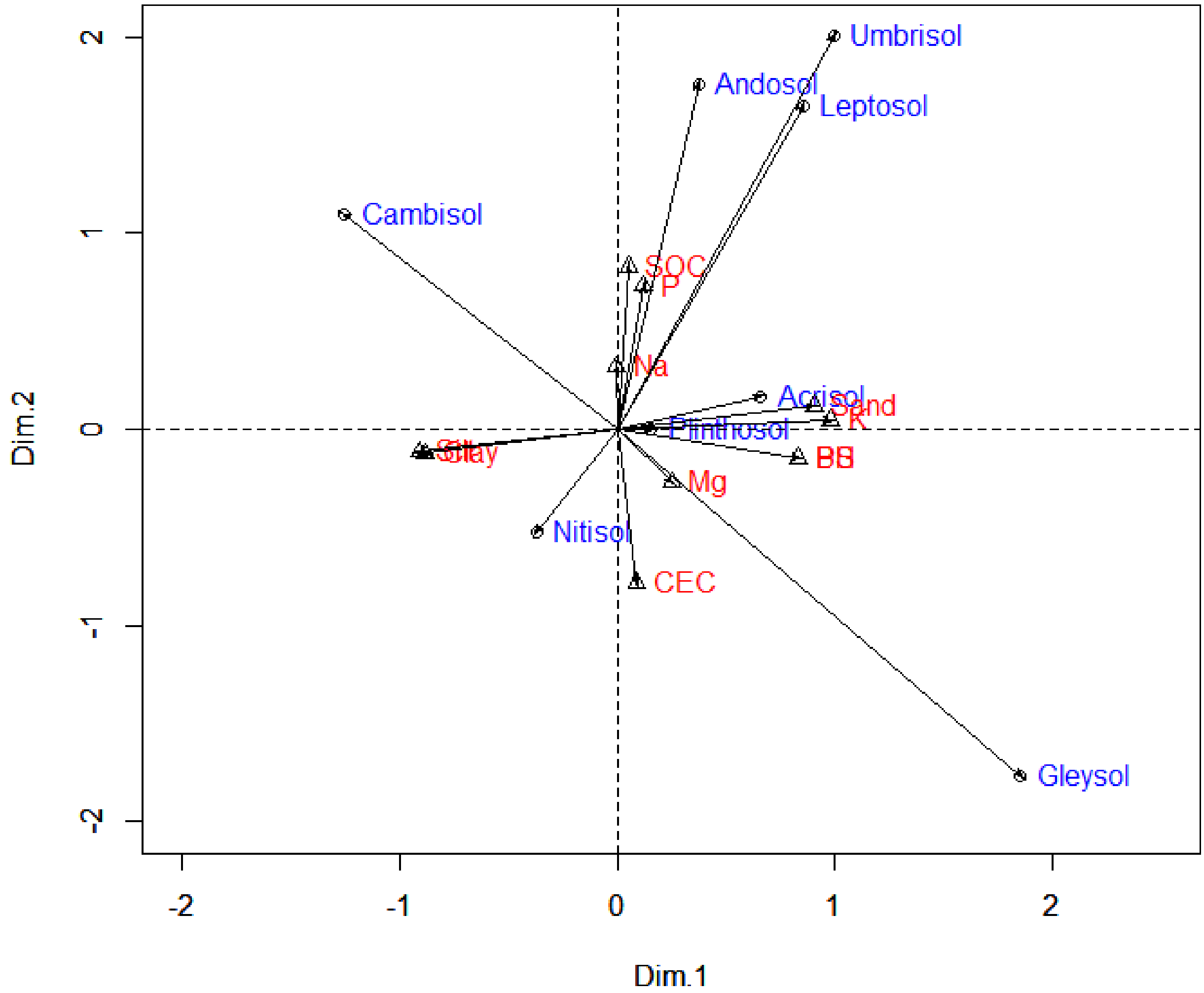

Figure 4.7. PCA biplot of soil properties

The silt and clay contents were strongly positively correlated together and negatively correlated to Sand, K, BS, and PH. Cambisols tended to be low in CEC, PH, Mg, and BS, while Gleysols were higher in these properties. Acrisols were characterised by high Sand and K contents. The soils in the study area were described by gradients defined by soil texture characteristics (Dimension 1) and SOC (Dimension 2).

4.1.2 Farming Systems and Soil Fertility Management Strategies

Under this second objective, farming systems and management practices are characterized. Next, socio-economic determinants of adoption of strategies related to soil fertility management practices are explored. To achieve this objective, descriptive statistics on demographic characteristics, farming systems practiced, soil fertility management practices, crop residue management strategies, are presented. Correlations between socio-economic variables and SFMP are performed using Fisher's exact and Welch's tests.

4.1.2.1 Demographic and socio-economic characteristics

Results of demographic characteristics are presented first, including age, education, household income and type of farming (

Table 4.7). The largest proportion of farmers included those in the age cohort (31-40 years), while 20-30 age group represented less than 10% of the sample. There were few farmers who did not attain formal education (3%) across the sample. Most of the farmers were primary (45%) and high school graduates (43%). In relation to agricultural income contribution, 35% of the farms experienced 51-75% income contribution. Agricultural income contributed more than half of house-hold income among 86% of all farmers. Most farmers practiced mixed crop-livestock farming (94%). The house-hold size averaged 5 members, while approximately 3 members were involved in farming activity per household. The mean annual income averaged Ksh 203,149.

Table 4.7. Major socio-demographic characteristics of farms in Mount Kenya East

Variable	Categories	Frequency (%)
Age categories	20-30	10(9.4)
	31-40	32(30.2)
	41-50	24(22.6)
	51-60	21(19.8)
	60+	19(17.9)
Education	None	3(2.8)
	Primary dropout	48(45.3)
	High school dropout	45(42.5)
	Middle level Graduate	7(6.6)
	Tertiary	3(2.8)
Gender	Male	57 (53.8)
	Female	49 (46.2)
Farming Income contribution	0-10%	1(0.9)
	11-25%	6(5.7)
	26-50%	8(7.5)

Variable	Categories	Frequency (%)
	51-75%	37(34.9)
	76-100%	54(50.9)
Farming type	Crop Farming	6(5.7)
	Both crop and livestock farming	100(94.3)
Farming experience (years)	<20	54(50.9)
	>20	52(49.1)
Family size		5.1
Members active in farming		2.7
Farm size (Ha)		1.3
Crop income/ year		197044.6
Livestock income/ year (Ksh*)		106208.9
Employment income		320000
Wages		124000
Business income		240000
Total income		271668.6

Values are presented as number of farmers and column percentages calculated within county (parentheses) for categorical variables. For numeric variables, values are means.

**1 Kenya shilling (Ksh)=0.0101 USD based on the average exchange rate at the time of data collection (March 2019)*

4.1.2.2 Farm characteristics

4.1.2.3 Major cropping systems practiced by farmers

Farmers practiced more than one form of cropping system on their farms (Table 4.8). Most of the fields were under mixed cropping. Pure stand cropping system was common for fields under such crops as tea.

Table 4.8. Major cropping systems practiced in Meru and Tharaka Nithi

Practice		Frequency	Percentage
Pure stand	Yes	41	38.7
	No	65	61.3
Mixed cropping	Yes	64	60.4
	No	42	39.6
Agroforestry	Yes	27	25.5
	No	79	74.5
Intercropping	Yes	8	7.5
	No	98	92.5
	Total	106	100

Values are presented as number of farmers and column percentages (parentheses)

4.1.2.4 Livestock distribution in the study sites

Farmers in the survey area keep various kinds of livestock on their farms (Table 4.9). The most common livestock included exotic dairy, goat and poultry which were most prevalently kept by farmers.

Table 4.9. Types and numbers of livestock kept by farmers in the study area

Livestock type	Frequency
Exotic dairy	2.7(67)
Cross dairy	2.0(3)
Indigenous	2.6(17)
Beef	2.6(11)
Goat	4.3(53)
Sheep	3.3(21)
Poultry	16.8(74)
Rabbit	5.8(4)
Pig	1.3(4)

Values are means followed by number of farmers (parentheses)

TLU=Tropical Livestock Units. Is an aggregation of the different types of livestock.

4.1.2.5 Soil fertility management practices

Farmers employ different strategies in managing soil fertility (Figure 4.8). The most important soil fertility management strategy among farming households included fertilizer and manure application, followed by agroforestry. Residue burn is the least deployed practice.

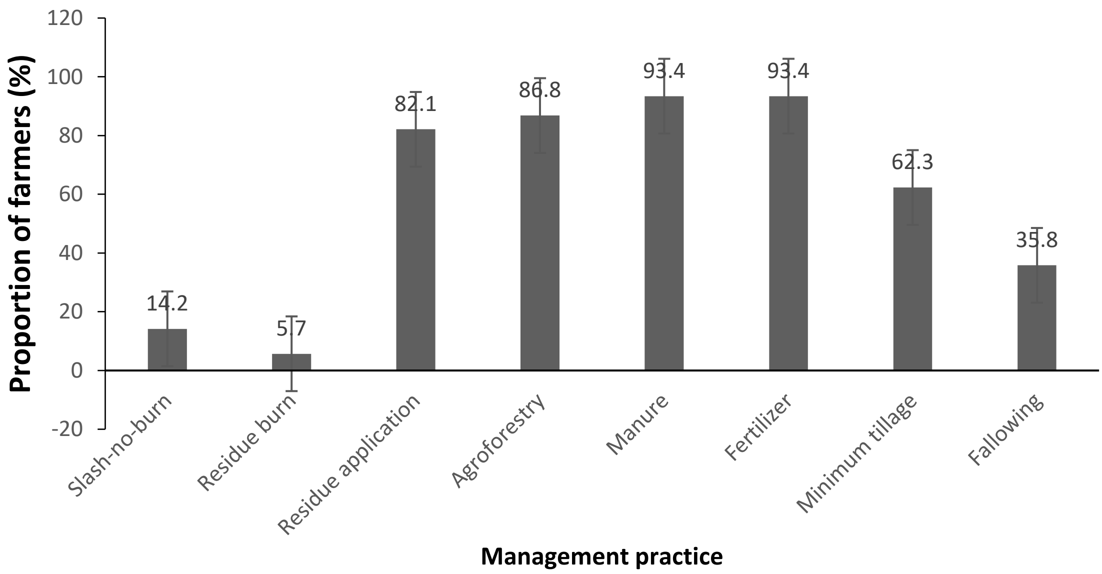

Figure 4.8. Different soil fertility management strategies practiced by farmers in the study area

4.1.2.6 Management of crop residues by farmers

Farmers manage crop residues from the harvested crops, in several ways (Figure 4.9). Majority of the households use crop residues as livestock fodder. Plant residues are also incorporated in the soil as well as used as a source of cooking fuel.

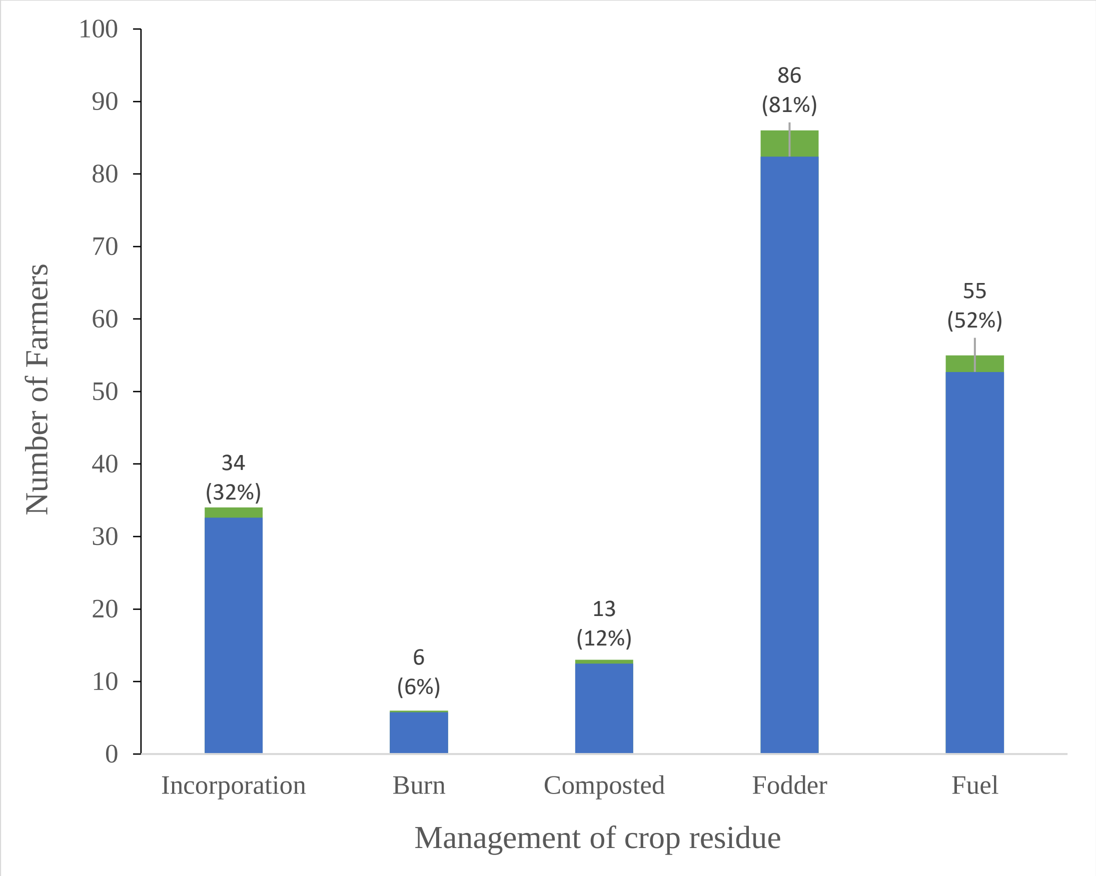

Figure 4.9. Crop residue management approaches used by farmers in Meru and Tharaka Nithi

4.1.2.7 Fertilizer and manure combination

Among the farmers who use fertilizer, majority of them (96%) also use manure (Table 4.10).

Table 4.10. The use of Fertilizer and manure in combination, among farmers in the study area

		MANURE APPLICATION		
		No	Yes	Total
FERTILIZER	No	4	3	7
	Yes	3	96	99
Total		7	99	106

4.1.2.8 Inorganic fertilizer application patterns

Majority of the farmers used fertilizer for both planting and topdressing (Figure 4.10). The rest of the farmers either only used mineral fertilizer for planting or top dressing due to inadequate resources.

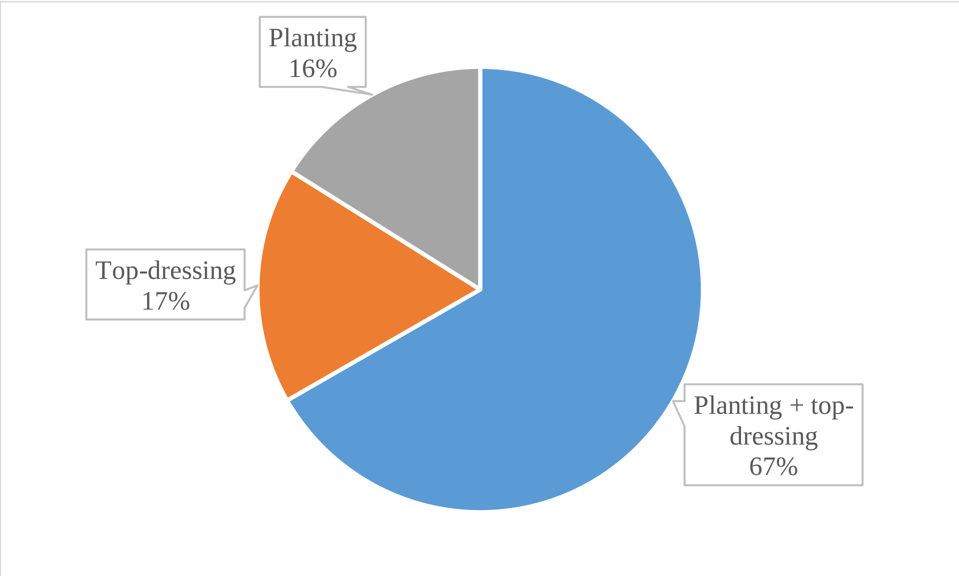

Figure 4.10. Fertilizer use patterns during planting and top dressing

The average fertilizer application rate was 76 and 61 kg ha^{-1} for planting and top dressing, respectively.

About 71% of farmers use inorganic fertilizers every farming season for planting and 61% for top-dressing (Figure 4.11). The rest of the farmers applied fertilizers only during the main season. The use of mineral fertilizers is reported to be unpredictable for nearly 30% of the farmers, as their action is largely determined by availability of resources at any given time. Of the farmers, who used mineral fertilizers, only 20% used the input in both cases (during planting and top dressing) every season.

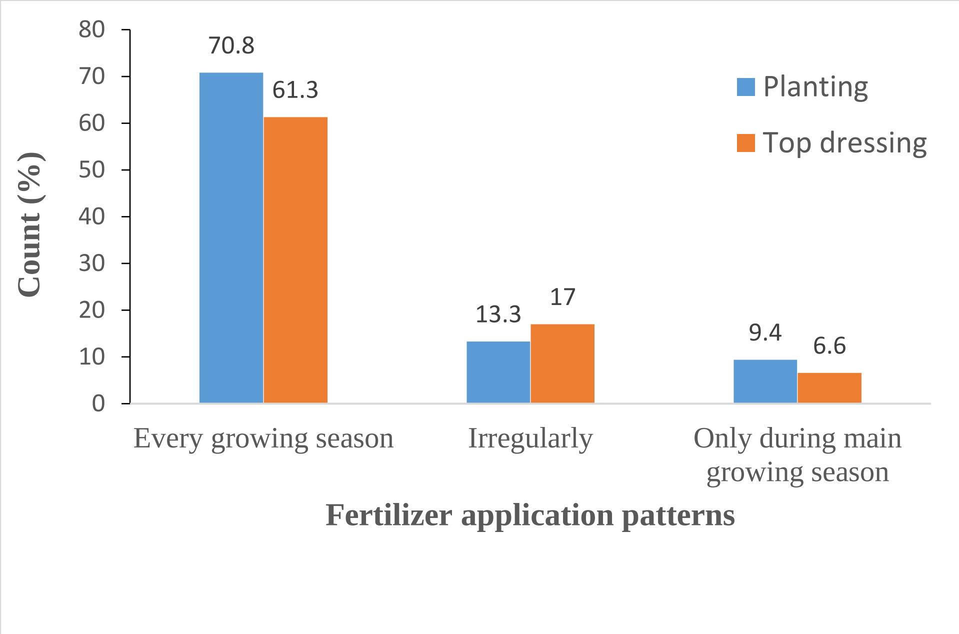

Figure 4.11. Farmer's fertilizer application patterns

4.1.2.9 Distribution of manure on the farm

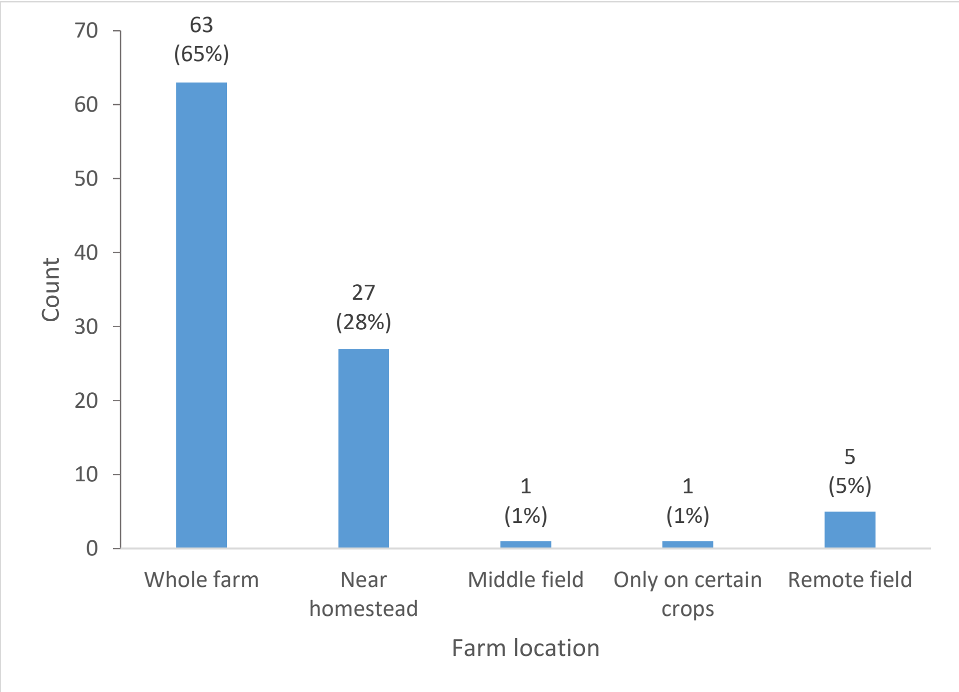

Figure 4.12. Manure application in Meru and Tharaka Nithi based on farm location

Farm application of manure varied across farming households (Figure 4.12). More than half of the farmers surveyed, applied manure on the entire cropping farm, while more than a quarter used manure only on the fields near the homestead.

4.1.2.10 *Fertilizer and Manure types and sources among sampled farmers in the study area*

Sources of fertilizer and manure

Most of the manure used on the farm (84.8%) is on-farm generated (Figure 4.13). This manure is however, in small amount and inadequate to meet the farm needs, and thus is supplemented from other sources including purchase from the local market and from neighbouring households. Acquisitions from neighbours can be at a cost or free, often in cases of relatives. Supplies of goat manure from neighbouring towns, especially Isiolo town, were common.

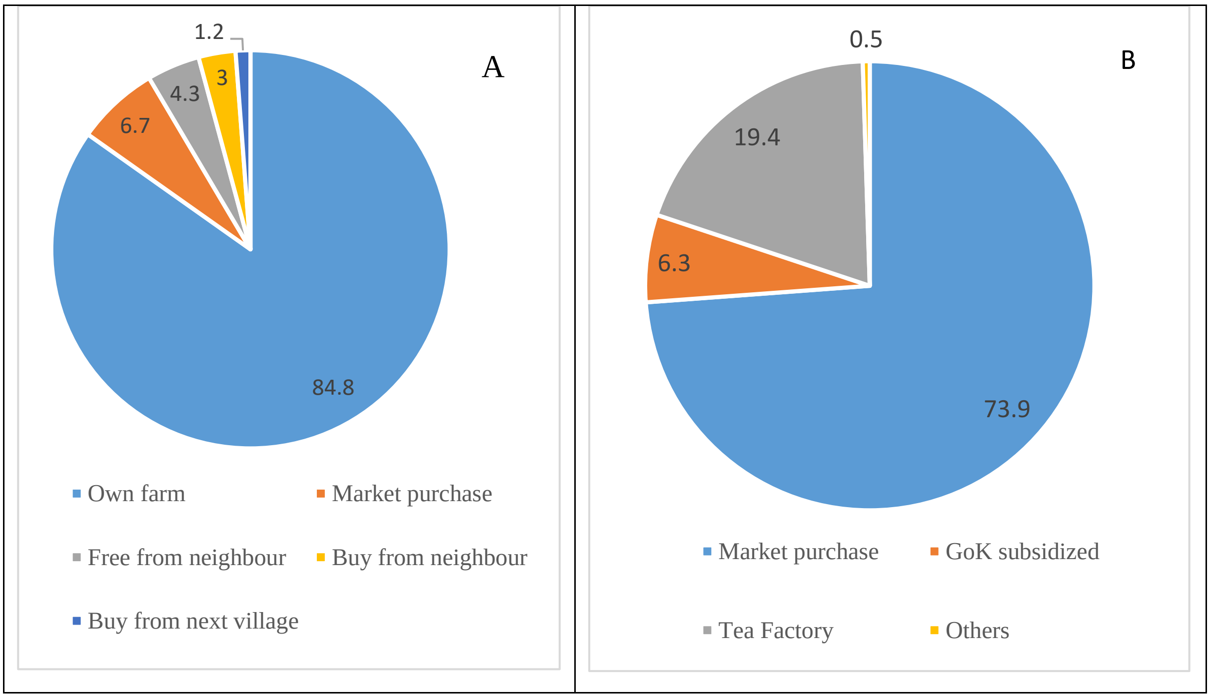

Figure 4.13. Sources of manure (A) and fertilizers (B) and and their proportional contribution to the total amount of fertilizer used on the farm. Values are in percentages

4.1.2.11 *Manure types and sources*

Farmers owned and accessed up to 4 different types of manure in the study area (Table 4.11). Most of the manure was generated on the household farms with only a few off-farm access cases. Cattle manure was used by 75 farmers of which 84% of the farmers generated the manure from their farms. Farmyard manure was used by 31 farmers, 87.1% of which was produced on-farm.

Table 4.11. Sources and types of manure used by farmers in Mount Kenya East region

Manure type and source	Owned	Free from neighbour	Buy local market	Buy from neighbour	Buy next village	Total
Cattle	84	4	5.3	5.3	1.3	75
FYM	87.1	6.5	3.2	0	3.2	31

Goat	84.1	0	13.6	2.3	0	44
Poultry	90.9	9.1	0	0	0	11

All the values except for the Total (which are absolute numbers) are proportion of farmers expressed in percentages.

4.1.2.12 Types of Fertilizers accessed by farmers

Different types of fertilizers used by farmers in the study area are presented (Figure 4.14). Diammonium phosphate (DAP 18:46:0) and Calcium ammonium nitrate (CAN 26%) are the most commonly used fertilizers during planting and top dressing, respectively.

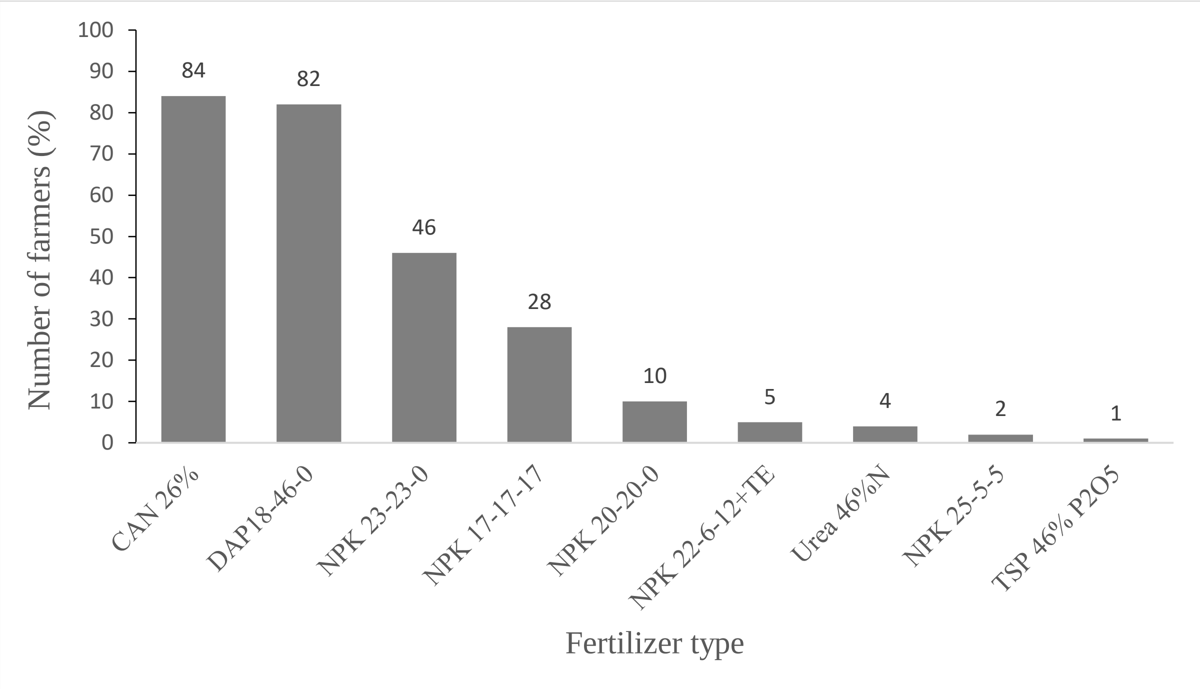

Figure 4.14. Proportion of households and the different kinds of fertilizers used.

4.1.2.13 Relationship between soil fertility management practices

Results of correlation matrix (Table 4.12) show strong positive associations between various practices, suggesting a complementarity relationship among them. There was a very strong significant correlation between inorganic fertilizer and manure application. The negative correlation between Residue burn and agroforestry could be explained by the fact that falling leaves from the farm trees are used on the farm as mulch.

Table 4.12. Correlations among the various SFMP based on farm household's usage patterns

Management practice	**Slash-no-Burn**	**Residue burn**	**Residue application**	**Agroforestry**	**Manure application**	**Minimum tillage**	**Fertilizer**	**Fallowing**
Slash-no-Burn	1	0.252***	-0.163*	-0.161**	-0.001	-0.075	0.108	0.261***
Residue burn		1	-0.098	-0.146*	-0.099	0.022	0.065	0.072
Residue application			1	0.326***	0.371***	0.347***	0.272***	-0.01
Agroforestry				1	0.569***	0.099	0.345***	0.001
Manure application					1	0.185**	0.541***	0.12
Minimum tillage						1	0.342***	0.095
Fertilizer							1	0.199**
Fallowing								1

****, **,*, Significant correlation at 1%, 5% and 10%, respectively.*

4.1.2.14 Combination of soil fertility management practices

Three groups consisting a set of technologies adopted by farmers were determined as visualized by the Ward linkage dendrogram (Figure 4.15). Cluster 1 consists of fertilizer and manure application and agroforestry. Fallowing, residue burn and slash-and-no-burn defined cluster 2. Cluster 3 was characterized by residue application and minimum tillage.

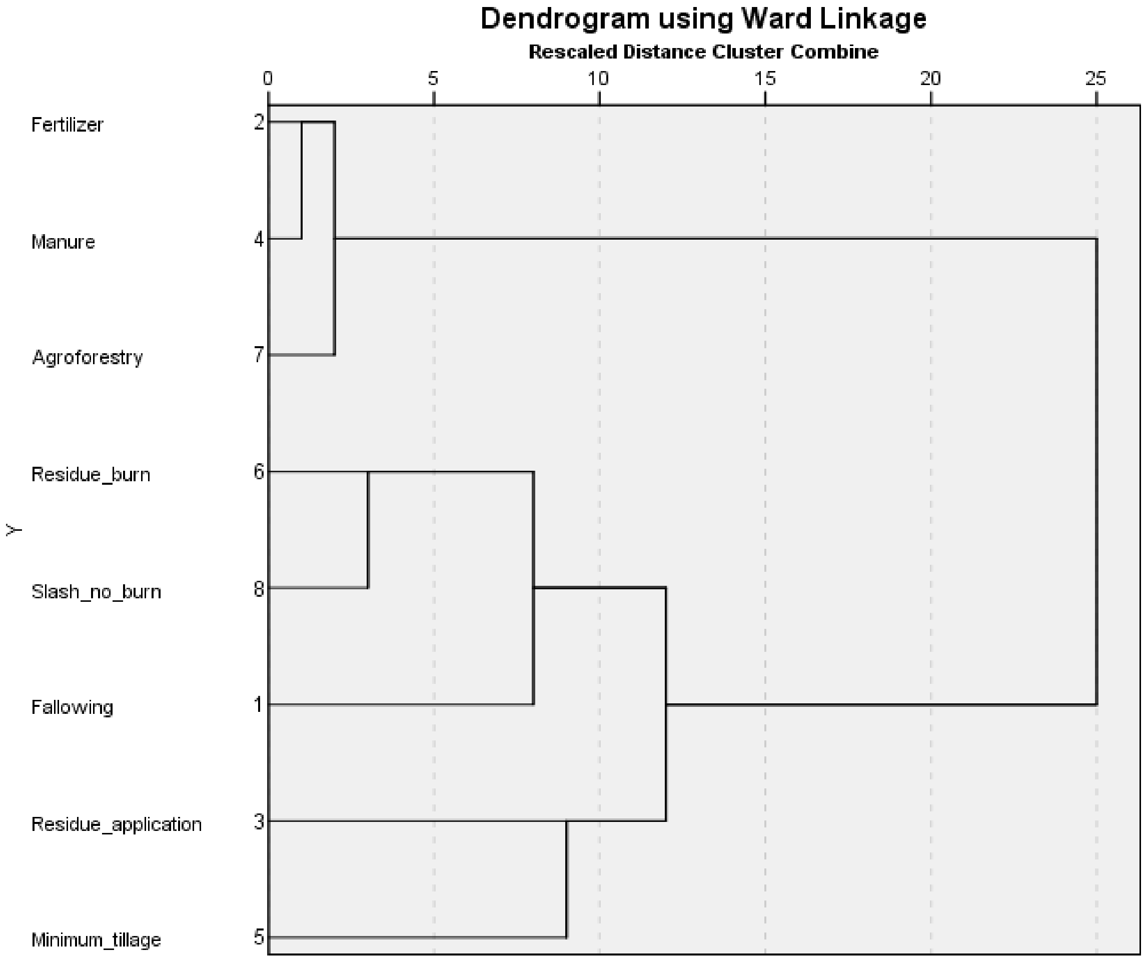

Figure 4.15. Dendrograms showing common combinations of ISFM technologies among farming households

4.1.2.15 Determinants of soil fertility management strategy

T-tests statistics were performed to determine the drivers of adoption of soil fertility management strategies. The results obtained from the Fisher's exact test (Table 4.13) and Welch's t test models (Table 4.14) are presented.

Table 4.13A. Fisher's Exact test of significance of explanatory variables

Variables	**Slash-no-burn**		**Residue burn**		**Residue app**		**Agroforestry**	
	Coef	**P>|z|**	**Coef**	**P>|z|**	**Coef**	**P>|z|**	**Coef**	**P>|z|**
Gender	0.105	0.403	-0.019	0.586	0.109	0.314	0.03	0.781
Age	0.218	**0.043****	-0.052	0.679	0.074	0.451	-0.031	0.495
Education	-0.205	**0.05****	-0.009	0.624	0.042	0.801	0.126	0.254
Farming as primary occupation	0.027	0.627	0.075	0.579	0.122	0.201	-0.119	0.603
Years in farming	0.089	0.413	-0.077	0.679	-0.083	0.454	-0.007	0.583
Location (County)	-0.169	0.109	-0.14	0.332	-0.134	0.237	0.158	0.18
Contact with extension	-0.246	**0.012****	-0.132	0.23	-0.137	0.204	-0.164	0.146

Access to soil information	-0.138	0.357	-0.083	0.509	-0.083	0.411	-0.05	0.637
Soil fertility info	-0.112	0.458	-0.111	0.587	-0.051	0.736	-0.12	0.251
Credit info	0.038	0.571	0.079	0.543	0.017	0.568	-0.16	0.126
Crop info	-0.148	0.182	-0.129	0.336	0.052	-0.554	0.2	**0.049****
Livestock info	0.202	**0.038****	0.019	0.66	-0.138	0.202	-0.156	0.146
Agribusiness info	0.08	0.538	0.049	0.789	0.093	0.448	0.077	0.562
Agribusiness info	0.053	0.758	0.053	0.758	0.154	0.295	0.058	0.617

Note: ***, **,*, Significant correlation at 1%, 5% and 10%, respectively.

Table 4.13B. Fisher's Exact test of significance of explanatory variables (Continuation)

Variables	Manure app		Fertilizer		Minimum tillage		Fallowing	
	Coef	**P>|z|**	**Coef**	**P>|z|**	**Coef**	**P>|z|**	**Coef**	**P>|z|**
Gender	0.134	0.245	0.058	0.701	0.137	0.167	0.101	0.318
Age	0.095	0.431	0.018	0.576	0.046	0.685	0.083	0.416
Education	0.048	0.709	0.048	0.709	0.146	0.162	-0.107	0.314
Farming as primary occupation	-0.081	0.527	-0.081	0.527	0.112	0.293	-0.125	0.277
Years in farming	0.033	0.521	0.033	0.521	0.024	0.843	-0.025	0.841
Location (County)	0.152	0.19	0.152	0.19	0.127	0.246	-0.06	0.641
Contact with extension	-0.15	0.235	-0.15	0.125	0.235	0.524	-0.178	**0.051****
Access to soil information	-0.034	0.547	-0.034	0.547	0.201	**0.049****	-0.125	0.321
Soil fertility info	-0.082	0.339	0.019	0.661	0.041	0.793	-0.076	0.591
Credit info	-0.174	0.131	0.044	0.511	0.015	0.565	0.107	0.325
Crop info	-0.136	0.172	-0.136	0.172	0.127	0.231	-0.107	0.331
Livestock info	0.154	0.138	0.154	0.138	-0.004	0.579	0.026	0.5
Agribusiness info	0.053	0.758	0.053	0.758	0.154	0.295	0.058	0.617

*Note: *, **, Significant at 5% and 1% significance level, respectively*

Among the various socio-economic and farm characteristics investigated, some had significant correlation with adoption of fertility management practices, while others were insignificant. The decision to implement slash-no-burn was related to the age of the household, family size and access to livestock husbandry information. There was a correlation between agroforestry and access to extension information, household size, number of livestock units. Adoption of minimum tillage was associated with access to soil information. Implementation of fallowing was correlated with contact with extension and household size. Adoption of manure application was associated with the household size and the number of livestock units. Both residue burn and crop residue application were correlated with farm size. There was a significant relationship between residue burn and income.

Table 4.14. Welch t test of significance of determinants of soil fertility management practices (continuous variables)

Variables	Slash-no-burn	Residue burn	Residue app	Agroforestry	Manure app	Fertilizer	Minimum tillage	Fallowing
On-farm labour	0.832	0.019**	0.237	0.022**	0.006**	0.012**	0.4	0.818
Household size	0.204	0.356	0.427	0.032**	0.032**	0.004**	0.642	0.366
Farm size	0.037**	0.000***	0.375	0.765	0.52	0.688	0.453	0.065
Household income	0.374	0.003**	0.139	0.827	0.839	0.824	0.818	0.815
TLU	0.176	0.548	0.876	0.000***	0.011**	0.143	0.012**	0.142

*Note: *, **, ***, statistically significant at 10%, 5% and 1% signignificance levelrespectively*

However, the application of ISFM needs to be adapted to the local environment. Farmers have different assets which determine how they can apply each of the pillars, and therefore exploring which practices make more sense depends on farmer's assets such as capital and labour. ISFM merges scientific and local knowledge while aiming at optimal use of available resources.

4.1.2.16 Drivers of uptake of inorganic fertilizer and manure

There was a significant positive correlation between maize crop and income and the decision to use fertilizer (Table 4.15). Other outcomes that were significantly associated with maize crop include planting with fertilizer, top dressing with fertilizer, planting plus top dressing with fertilizer, and the use of manure. Meaning that maize had higher chances of receiving the mentioned treatments as compared to other crops. Income was significantly correlated with the adoption as well as use of fertilizer for planting (Table 4.16). Contact with extension providers was significantly associated with the use of fertilizer for planting and manure application. Education level of the household head and the perceptions about poor quality fertilizer had a significant association with the farmer's decision to top dress their crops. Lack of knowledge on better fertility practices and the size of livestock unit were significantly correlated to the use of manure.

Table 4.15. Fisher's Exact test of significance of determinants of inorganic fertilizer and manure use

Variables	Use fertilizer		Fertilizer plant		Fertilizer top dress		Fertilizer Plant+topdress		Every season		Manure appl	
	Coef	P>|z|	Coef	P>|z|	Coef	P>|z|	Coef	P>|z|	Coef	P>|z|	Coef	P>|z|
Education	-0.061	0.717	0.062	0.717	0.237	0.051**	0.13	0.265	0.1	0.432	0.022	1
Maize	0.434	0.000***	0.434	0.000***	0.584	0.000***	0.889	0.000***	0.114	0.318	0.242	0.021**
Tea	0.011	1	-0.011	1	0.067	0.688	0.141	0.289	-0.102	0.452	0.002	1
Coffee	0.049	1	0.049	1	-0.087	0.391	0.1	0.569	-0.075	1	0.052	1
Expensive fertilizer	0.095	0.441	0.095	0.441	0.022	1	0.019	0.53	0.062	0.394	0.117	0.253
Soil testing	0.15	0.196	0.15	0.196	0.03	1	0.007	1	0.067	0.753	0.086	0.404
Limited Manure	0.041	0.521	0.041	0.521	0.034	1	-0.055	0.69	0.137	0.195	0.093	1
lack of fertility skills	0.156	0.133	0.156	0.133	0.09	0.467	-0.024	0.774	0.061	0.727	0.223	0.043**
Limited subsidy	0.049	1	0.049	0.788	0.072	1	0.1	0.569	0.062	0.492	0.052	1
Poor fertilizer quality	0.085	0.383	0.085	0.383	-0.239	0.043**	0.044	0.643	0.093	1	0.075	1
Extension contact	0.178	0.134	0.221	0.047**	0.003	1	0.031	0.824	0.045	0.793	0.198	0.040**

“*”,”**”,”***” significant at 0.1, 0.05 and 0.01 respectively

Table 4.16. Welch's t-test of significance of determinants of inorganic fertilizer and manure use

Welch t-test p-values					
Variables	Manure app	Fertilizer use	Fertilizer for planting	Fertilizer top dress	Every season
Farm size	0.037**	0.574	0.72	0.162	0.311
Household income	0.839	0.013**	0.013**	0.453	0.198
TLU[a]	0.011	0.143	0.254	0.399	0.953

“”,”**”,”***” significant at 0.1, 0.05 and 0.001 respectively*

[a]TLU= Tropical Livestock Units (livestock numbers converted to a common unit)

4.1.3 Comparing Farmers' Soil Fertility Assessment and Scientific Measurements

The third objective of this research was to determine local indicators of soil fertility and compare scientific and farmers' soil fertility assessment. In this section, frequencies of soil fertility indicators and the indicator ratings are presented. Results of Factor Analysis (FA) of soil quality scores are shown. Analysis of laboratory soil properties measurements is presented. This is followed by presentation of results comparing farmer's soil classification with scientific soil quality index (SQI).

4.1.3.1 Farmers' indicators of soil fertility

Descriptive statistics of soil fertility indicators used by farmers to classify fertile and infertile soils, are presented (Table 4.17).

High fertility plots were characterised by dark coloured soils (94%), while they were light coloured in poor sites. Most farmers also recognised earthworms as key indicators of fertile soils (86%) while indicator weeds were shown by 91% of farmers. In terms of topography, valley bottoms indicated fertile fields (90%), while upper slopes were mostly infertile sites. Fertile soils were also characterized by high water holding capacity and good soil workability. For infertile plots, the most important indicators included low yield, yellow leaves, slow growth, light coloured soils, soils with low water-holding capacity, and tilling difficulty.

Table 4.17. Descriptive soil quality indicators among farmers for high and low fertility fields

Indicator /characteristic		High fertility		Low fertility	
		Frequency	Percentage	Frequency	Percentage
Colour	Brown	2	2.9	13	18.8
	Dark	65	94.2	2	2.9
	White/pale/light	2	2.9	43	62.3
	Red			11	15.9
Earthworms	Numerous worm casts	59	85.5	1	1.4
	Moderate worm casts	8	11.6	1	1.4
	Fewer worm casts	2	2.9	67	97.1
Indicator weeds	Present	63	91.3	51	73.9
	Not present	6	8.7	18	26.1
Topography	Valley bottom slopes	62	89.9	6	8.7
	Lower middle slope	3	4.3	6	8.7
	Upper slopes	4	5.8	57	82.6
Water holding capacity	High	63	91.3	3	4.3
	Moderate	2	2.9	1	1.4
	Low	4	5.8	65	94.2
Workability	Very easy to till	40	58	9	13

Indicator /characteristic		High fertility		Low fertility	
		Frequency	Percentage	Frequency	Percentage
	Moderately easy to till	22	31.9	4	5.8
	Difficult to till	7	10.1	56	81.2
High yields	High yields	69	100	-	-
Leaf colour	Green leaf colour	69	100	-	-
	Yellow leaves	-	-	69	100
Growth	Fast growth	69	100	-	-
	Stunted growth	-		69	100

4.1.3.2 Soil Fertility indicator ratings

All indicators recorded significantly higher soil quality ratings in fertile soils compared to infertile soils. The results indicated that fertile soils recorded darker soils, more earthworms, better crop growth, favourable indicator weeds, greener leaf colour (for crops), higher soil water holding capacity, soil workability and crop yields (Figure 4.16).

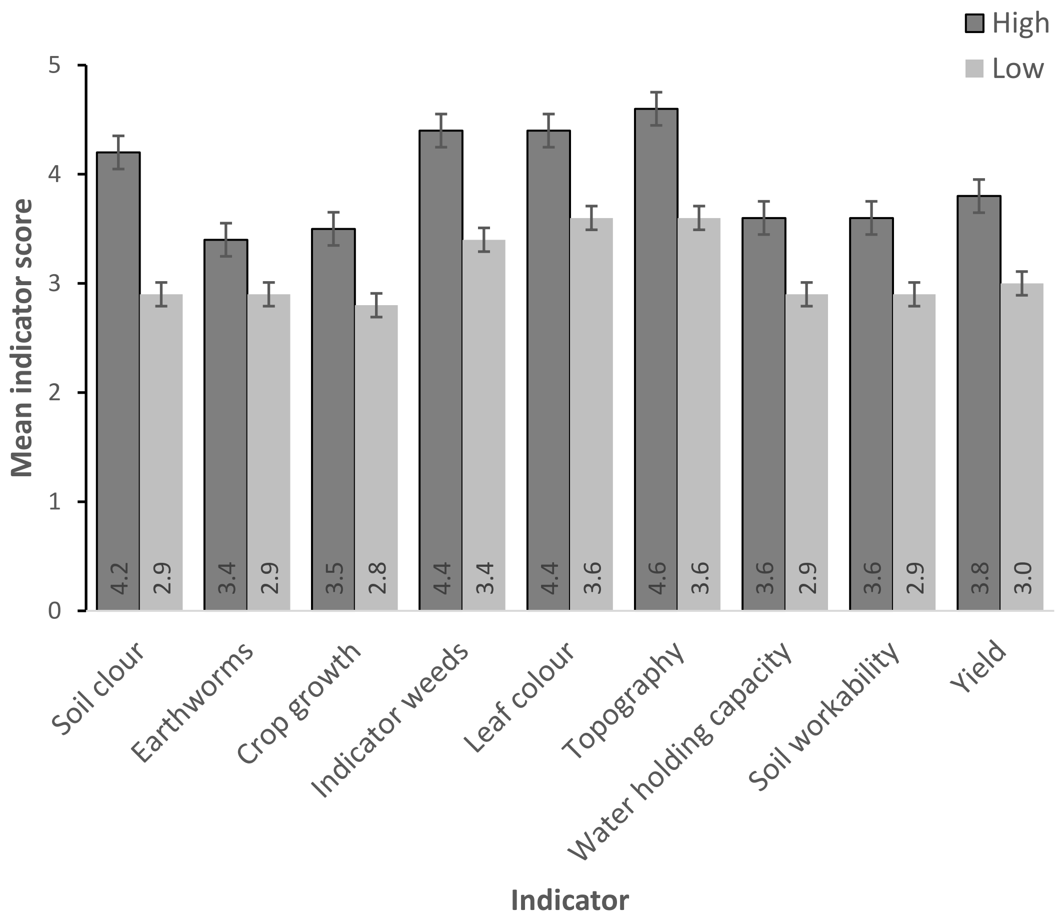

Figure 4.16. Mean soil quality ratings for high and low and fertility plots in Mount Kenya East region

4.1.3.3 Factor Analysis (FA) of Soil Quality Scores

Soil quality factor loadings showed that the first component was dominated by leaf colour, indicator weeds, soil colour and topography colour score loadings. This data structure represented the farmers' soil quality perceptions in terms of associations between the variables. The first component was manifested by high loadings in leaf colour and indicator weeds score, while the second factor was a description of crop growth, earthworms and yield score associations. The third component represented a description of soil physical indicators (Table 4.18).

Table 4.18.Varimax-rotated factor analysis for descriptive soil quality scores

	Component			
Soil indicator score	**1**	**2**	**3**	**Communalities**
Leaf colour score	0.858			0.768
Weeds score	0.723			0.630
Soil colour score	0.695			0.598
Topography score	0.428			0.343
Crop growth score		0.851		0.877
Earthworms score		0.832		0.698
Yield score		0.606		0.583
Soil water holding capacity score			0.897	0.812
Soil workability score			0.802	0.809
Eigen values	**2.8**	**2.0**	**1.3**	
% of variance	**31.3**	**21.7**	**14.9**	
Cumulative variance	**31.3**	**53.1**	**68.0**	

4.1.3.4 Laboratory Soil Fertility Properties and Soil Quality

The comparison in soil fertility measures between high and low fertile plots was undertaken using Independent sample test (Levene's Test for Equality of Variance). There were significant differences in key soil properties including soil pH, SOC, moisture and available-N in high and low fertility soils (Table 4.19). Soils were slightly more acidic in low fertile fields, compared to fertile soils.

Table 4.19. Independent Samples t-test results of mean soil fertility measures for topsoils in high and low fertility soils

Soil parameter	Fertility	N	Mean	Std. Devi	Std. Error Mean	P-value (Levene's test)
K(Cmol/kg)	Low	27	0.8574	0.2952	0.0461	
	High	41	0.8994	0.2361	0.0454	0.518
Mg (Cmol/kg)	Low	28	0.7313	0.4149	0.0784	
	High	41	0.7974	0.4746	0.0741	0.542

Ca(Cmol/kg)	Low	28	1.7887	0.8690	0.1642	
	High	41	2.0069	0.7502	0.1172	0.284
Na (Cmol/kg)	Low	27	0.0149	0.0390	0.0062	
	High	40	0.0088	0.0315	0.0061	0.482
CEC (cmol/kg)	Low	28	9.5642	3.1663	0.5984	
	High	41	9.8408	4.8049	0.7504	0.774
BS%.	Low	28	16.8466	6.5856	1.2446	
	High	41	18.0124	7.4640	1.1657	0.497
Moisture %	Low	28	3.6583	1.7930	0.2800	
	High	41	4.5357	1.8250	0.3449	**0.051**
Sand (%)	Low	28	25.6786	8.5551	1.6168	0.799
	High	41	26.2439	9.6819	1.5121	
Silt (%)	Low	28	38.7143	5.8046	1.0970	0.590
	High	41	37.9024	6.5567	1.0240	
Clay (%)	Low	28	35.7500	6.6479	1.2563	0.903
	High	41	35.9512	6.8628	1.0718	
AL-P2O5	Low	28	599.9683	334.1521	52.1858	0.459
(mg/kg)	High	41	660.6571	331.2367	62.5978	
AL-K2O	Low	28	47.2500	116.9145	22.0948	0.950
(mg/kg)	High	41	48.8780	86.9995	13.5870	
pH.H2O.	Low	28	5.2643	0.6924	0.1309	**0.032**
	High	41	5.6488	0.7464	0.1166	
	Low	27	0.8966	0.5253	0.1011	0.032
OC (%	High	41	1.7247	0.5177	0.0809	
Ava N (mg/Kg)	Low	22	31.9091	26.3365	5.6150	0.045
	High	33	19.5152	18.5171	3.2234	

4.1.3.5 Soil quality indices (SQIs)

Additive SQI

The results for additive SQI are presented (Table 4.20). The additive SQ1 ranged from 3-9, averaging 6.3 in the topsoils. On a parameter basis, the SQI for soil organic carbon averaged 0.4 while available P was 0.2. The soil CEC averaged 1.5, while available N was relatively low.

Table 4.20. Additive SQI for selected soil fertility indices for topsoils (0-20 cm)

Parameter	Minimum	Maximum	Mean	Std. Deviation
Sand	0	1	0.03	0.169
Soil pH (Water)	0	1	0.52	0.503
Soil organic carbon	0	1	0.41	0.495
Exchangeable calcium	1	2	1.01	0.120
Exchangeable Potassium	0	2	0.93	0.312

Exchangeable magnesium	0	2	1.62	0.788
Available P	0	2	0.22	0.481
Soil CEC	0	2	1.49	0.740
Available N	0	1	0.04	0.205
Additive SQI	3	9	6.28	1.454

Factor analysis SQI (FA-SQI)

Results for the rotated factor analysis model for the multivariate SQI derivation are presented in (Table 4.21).

Factor 1 was defined by SOC, CEC, available P, sand and available N. Exchangeable Ca and pH characterized component 2, while component 3 was defined by Exchangeable K and Mg.

Table 4.21. Varimax-rotated factor analysis for the FA-SQI derivation

	Factors			
Parameter	**1**	**2**	**3**	**Communalities**
Soil organic carbon	0.853			0.759
CEC	0.709			0.605
Available P	0.635			0.596
Sand	0.604			0.624
Available N	0.577			0.608
Exchangeable Ca		0.896		0.838
pH Water		0.861		0.814
Exchangeable K			-0.735	0.549
Exchangeable Mg			0.555	0.544
Eigen values	**2.5**	**2.3**	**1.2**	
% of Variance	**27.6**	**25.4**	**12.9**	
Cumulative %	**27.6**	**53.0**	**66.0**	

4.1.3.6 Linkage between farmer and measured soil quality indicators

Regarding the regression between additive soil quality index and the farmer-descriptive SQI, there was a positive relationship indicating that the additive SQI increased with farmer-descriptive SQI in both high (y=1.94+0.29x, R^2=25%) and low fertility plots (y=3.7+0.082x, R^2=4%), though this relationship was stronger in high quality soils compared to low quality soils, as shown by their regression functions (Figure 4.17A). In fertile fields, increasing the additive SQI by one unit was associated with an average increase of 0.29 units in the farmer-descriptive SQI. The pooled regression model was positively significant. The farmer-descriptive SQI was significantly and positively related with the FA-SQI (y=3.6***+0.82x***, rsq=90%) (Figure 4.17A). In regard to the FA-SQI, a unit increase in the multivariate index led to an average increase of 1.2 units in the farmer-descriptive SQI (Figure 4.17B).

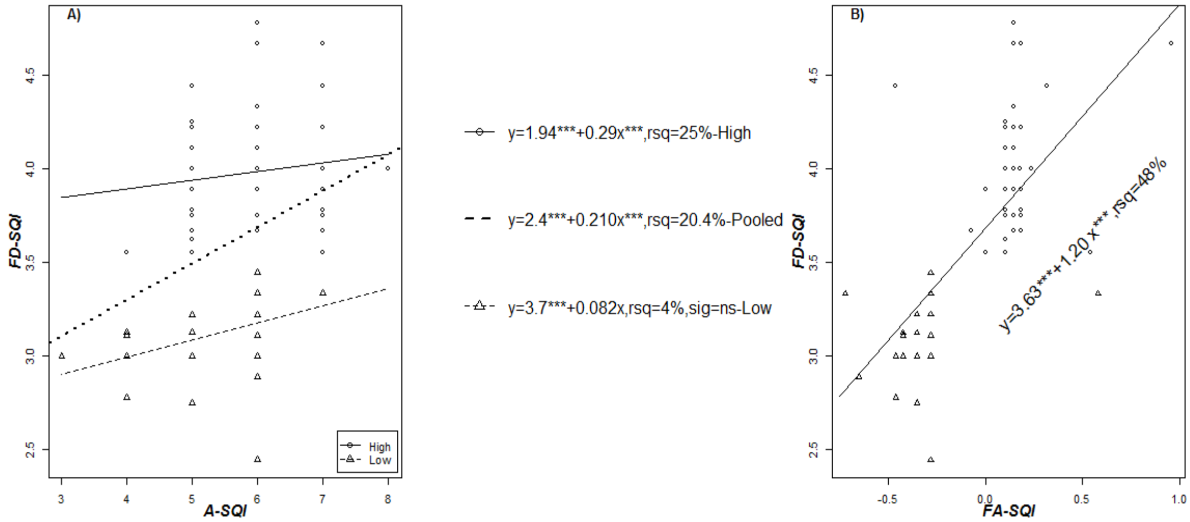

Figure 4.17. Relationship between quantitative and qualitative soil quality indices in the study area (0-20 cm depth). Farmer-descriptive SQI is correlated against additive SQI (A) and Factor analysis-generated SQI (B).

4.1.4 Influence of Farm Management Practices on Soil Fertility.

Under the fourth objective, the correlation between farm management practices and laboratory soil characteristics, is first examined. This is followed by farm classifications based on household's socioeconomic characteristics, farm management practices, and scientific soil properties. Prior to classification, respective variables were submitted to PCA (CATPCA and FA) to determine influential parameters for inclusion in the cluster analysis procedure. Differences in characteristics between clusters (based on cluster membership variable) in each classification, were examined. The final cluster analysis was performed with variables that were identified as highly influential by CATPCA and FA techniques. A total of 9 variables that loaded highly in each of the three components (or factors, in the case of FA) for farm management characteristics, socio-economic attributes and soil characteristics were submitted in the CA model.

4.1.4.1 Correlating Farm practices with soil properties using ANOVA

ANOVA was performed in R environment to determine significance of associations between the various soil fertility management practices and soil properties and results presented (Table 4.22).

Table 4.22.P-values based on ANOVA to determine the relationship between management practices and soil properties

Variables	Fertility (Fertile/infertile)	Agroforestry (yes/no)	Fallowing (yes/no)	Farming type (mixed/crop)	Manure use (Yes/no)	Minimum tillage(yes/no)	Mulching (yes/no)	Residue retention (yes/no)	Land use	Slope
BS	0.287	0.087	***0***	0.233	0.049	0.702	0.689	0.623	0.108	0.742
CEC	0.243	**0.013**	0.602	0.871	0.836	**0.043**	**0.045**	**0.025**	0.108	0.765
Ca	0.507	**0.003**	**0.006**	0.4	***0***	0.065	0.057	0.606	0.115	0.684
K (exch.)	0.262	0.456	**0.017**	***0***	***0***	**0.002**	0.781	0.978	0.662	0.184
Mg	**0.031**	0.055	**0.014**	***0***	***0***	0.513	**0.053**	0.639	0.227	0.716
Na	0.382	**0.002**	**0.002**	0.337	***0***	0.142	***0***	***0***	***0***	0.55
OC	**0.054**	**0.051**	0.825	0.787	0.435	**0.019**	0.936	0.085	**0.006**	0.084
pH (H_2O)	0.447	***0***	***0***	0.168	***0***	0.184	0.135	0.545	**0.002**	**0.046**
K(extract.)	0.671	0.687	0.22	0.585	0.572	0.216	0.959	0.805	0.585	**0.033**
Clay	0.623	**0.002**	0.692	0.851	0.46	0.743	0.815	0.209	0.263	0.257
Silt	0.056	0.393	0.499	0.653	0.824	0.875	0.575	0.871	0.887	0.06
Sand	**0.042**	**0.003**	0.496	0.694	0.666	0.755	0.597	0.267	0.739	0.064
Moisture	0.475	0.668	0.181	0.569	0.476	0.504	0.522	0.089	0.296	0.577
Phosphorus	0.754	***0***	0.141	0.262	0.717	**0.013**	**0.038**	0.115	0.716	0.076
Ava. N	0.071	0.341	0.836	**0.003**	0.753	0.32	**0.036**	0.275	**0.002**	0.516

Note: Bolded values=Significant at 0.05, Bolded and italicized=Significant at 0.001 significance level.

The management practices that were shown to influence soil quality include agroforestry, fallowing, manure application, minimum tillage and crop residue retention.

Base saturation

There was a significant correlation between base saturation and fallowing ($p<0.01$) and manure application ($p<0.05$). Farms that practised fallowing at some point, had higher base saturation compared to the farms where fallowing has never been adopted (Table A 5). Farms that applied manure had higher base saturation compared to those farms where manure was not applied (Table A 4).

Cation exchange capacity (CEC)

There was a positive significant association between CEC and agroforestry ($p<0.01$), minimum tillage ($p<0.05$), mulching ($p>0.05$) and residue retention ($p<0.05$). CEC was higher in farms with agroforestry (Table A 6), minimum tillage (Table A 7) and mulching (Table A 8).

Exchangeable cations

Among the measured exchangeable cations, calcium had a significant correlation with agroforestry ($p<0.01$), fallowing ($p<0.01$), manure ($p<0.01$), minimum tillage ($p<0.05$) and mulching ($p<0.05$). Ca^{2+} was higher in farms with agroforestry (Table A 6), fallowed farms (Table A 5) and farms with manure application (Table A 4). Ca^{2+} was higher infields with mulching (Table A 8) and minimum tillage (Table A 7).

Exchangeable potassium (K^+) had a significant association with fallowing ($p<0.01$), type of farming (($p<0.01$), manure application ($p<0.01$) and minimum tillage ($p<0.01$). K^+ was higher in fallowed farms (Table A 5), mixed crop-livestock farms (Table A 10) and farms that embraced minimum tillage (Table A 7).

Magnesium (Mg) was influenced by Agroforestry ($p<0.05$), fallowing ($p<0.01$), type of farming ($p<0.01$), manure application ($p<0.01$) and mulching ($p<0.05$). Mg was higher in farms with agroforestry (Table A 6), fallowing (Table A 5) and manure application (Table A 4). Mixed crop-livestock farms had higher Mg compared to crops-only farms (Table A 10).

Sodium (Na) measurements significantly correlated with agroforestry ($p<0.01$), fallowing ($p<0.01$), manure application ($p<0.01$), mulching ($p<0.01$), residue retention ($p<0.01$), and land use type (cultivated crop) ($p<0.01$). Na level was lower in fields with agroforestry (Table A 6) fallowing (Table A 5) and mulching (Table A 8). Fields that applied manure, mulching and crop residues had lower Na levels.

Organic Carbon (OC)

OC was significantly associated with agroforestry ($p<0.05$), minimum tillage ($p<0.05$), residue retention ($p<0.05$) and land use ($p<0.01$). In regard to land use, samples from tea plots had higher OC.

pH

There was a significant correlation between pH (water) and agroforestry ($p<0.01$), fallowing ($p<0.01$), manure application ($p<0.01$) and land use ($p<0.01$). pH was higher in farms with agroforestry, fallowing and manure application. The pH was higher on on legume-cultivated and lowest on tea farms (Table A 11).

Particle size proportions

Both clay and sand proportions had a significant association with agroforestry ($p<0.01$). ÍHigher clay proportion was registered in farms without agroforestry (47%) than farms with agroforestry (35%). Sand proportion was higher in farms without agroforestry (41%) than farms with agroforestry (26%).

Available phosphorus and potassium

Available phosphorus was significantly associated with agroforestry ($p<0.01$), minimum tillage ($p<0.01$) and mulching ($p<0.05$). Farms with agroforestry, minimum tillage and mulching had higher levels of P.

Available Nitrogen

Available N was associated with the type of farming ($p<0.01$), mulching ($p<0.05$) and land use ($p<0.01$). Mixed crop-livestock farms were high in N levels (Table A6). Tea plantation farms had higher N while legume fields had the lowest N (Table A 11).

Soil nutrients and DAP application rates in Meru and Tharaka Nithi

Since nearly all the farmers used fertilizer, the question on whether on whether fertilizer was applied, was excluded from the previous analysis. Instead, the influence of the application rate of one of the mostly used fertilizers (DAP), on soil quality, is examined (Figure 4.18). The following analysis indicates that DAP fertilizer application rate increased the soil nutrients for soil available phosphorous, soil available N, and soil organic carbon. The soil pH tended to increase slightly.

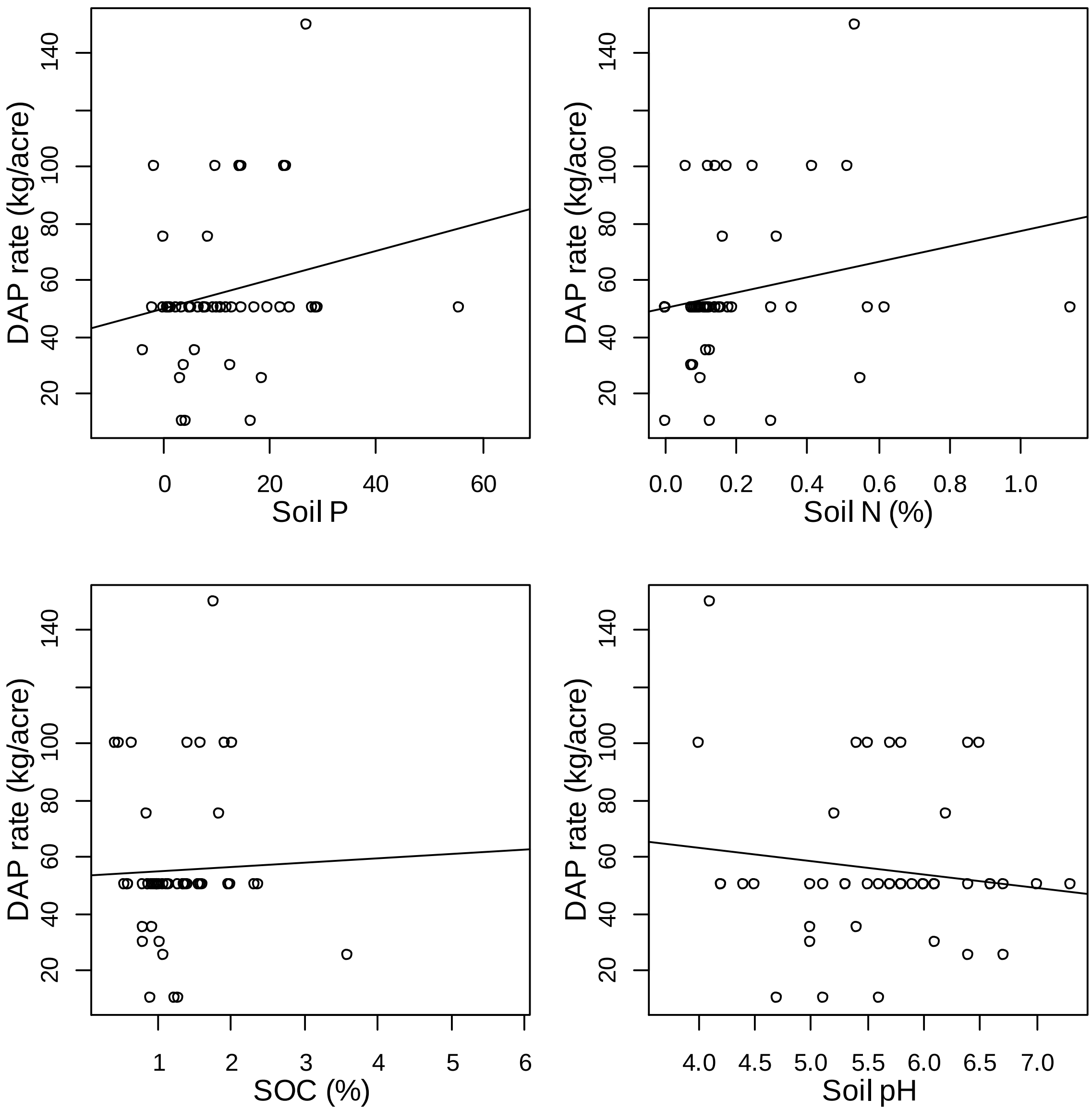

Figure 4.18. Association between Soil nutrients and DAP application rates

4.1.4.2 Farm classification

In this section, classification of farms (or farm typologies) is undertaken, using several techniques including Principal component analysis (PCA) and cluster analysis (CA). Three classification systems were generated: 1) households' socio-economic characteristics-based classification; 2) farm management practices-based classification; and 3) laboratory soil properties-based classification. PCA and CA have been widely used to classify farms

(Bidogeza et al., 2009; Tittonel et al., 2011). Prior to classification, respective variables in each case were subjected to data reduction using appropriate PCA techniques to predict the number of homogenous groups in the data sets (Dossa et al., 2011; Tittonell et al., 2010).

4.1.4.2.1 Principal component analysis of socioeconomic variables

All the 17 socio-economic variables (see Table 3.3) were submitted to the model with the number of dimensions retained at default (2). However, the two-dimensional solution accounted for only 39.3% of the variance (not plausible), implying that more information could be provided with additional dimensions. While 6 components were desirable (eigenvalues greater than 1 and accounting for more than 60% variance), the 4th and 5th components had low Cronbach's alpha scores (low reliability). Dimension was then set at 4 and CATPCA performed again. This time, the 4th component had only one variable with a loading score of >0.4. The results for the final analysis which was run based on 13 variables and with 3 dimensions, are displayed (Table 4.23). Some variables that were initially included in the model were omitted from the repeat analyses due to high loading scores in more than one principal components. These variables include gender, farming experience, family size and access to agribusiness training.

Table 4.23. Principal component loadings of household socio-economic variables based on CATPCA analysis using variable principal normalization

Variable	**Dimension**			
	1	**2**	**3**	**Total**
Extension contact	**0.856**			0.548
Soil info	**0.537**			0.662
Siol testing	**0.767**			0.454
Credit info	**0.539**			0.208
CropHusb	**0.733**			0.628
Animal_husb	**0.62**			0.255
Education		**0.69**		0.389
TotIncome		**0.444**		0.773
Age		**-0.477**		0.302
FarmOccup		**0.579**		0.598
Farmsize			**0.741**	0.309
TLU			**0.593**	0.577
Workforce			**0.71**	0.529
Cronbach's Alpha	**0.708**	**0.455**	**0.413**	**.909**[a]
Total (Eigenvalue)	**2.889**	**1.724**	**1.617**	**6.231**
% of Variance	**22.226**	**14.089**	**13.891**	**50.727**

a. Total Cronbach's Alpha is based on the total Eigenvalue.

Roughly 50% of the household variability was explained by the first 3 PCs. The first PC was associated with variables related to access to agricultural information. Education level of household head, total family income registered high positive loadings with PC2. Question on whether farming was the primary occupation for the household head, had high positive loading too, for this component. On the other hand, the age variable loaded negatively high. The third component was associated with farm size, number of livestock and family workforce, all of which loaded positively high. Considering their independence, these dimensions constitute a good starting point for a consistent categorization of households. Two-dimensional component loading plots (Figure 4.19) were generated to provide a visualization of the relationships among the socio-economic factors.

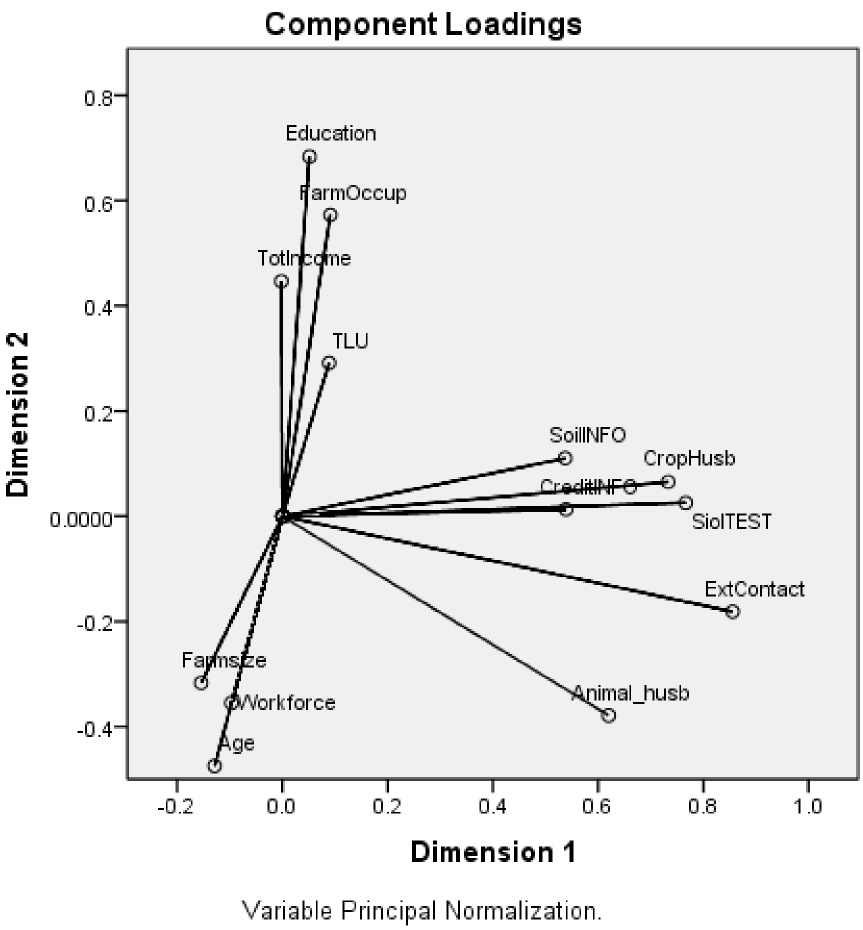

Figure 4.19. Correlation biplot showing the relationship between socioeconomic variables.

Small angles between the vectors represent a strong positive correlation. An angle of about 90 degrees indicates absence of correlation, while large angles of close to 180 degrees suggest a negative correlation. The length of the vectors is directly proportional to the influence of the variable (communality). There was a strong correlation among the information-related variables, namely contact with agricultural extension, access to information on soil, crops, animals and credit. Figure 4.19 suggests that a priori 3 classes of household characteristics can be identified in the study area following the associations between the determinant variables.

4.1.4.2.2 Principal component analysis of management practices

Field management characteristics were distributed into three principal components through CATPCA using principal normalization. CATPCA was first performed with all the 15 farm management-related variables, with 2 default dimensions. The resulting solution accounted for only 40% of the variance, which is considered too low, and thus a need for more dimensions. The analysis was repeated with dimensions number set at 10. The first 4 components had eigenvalue greater than 1, and accounted for 63% of the variance. However, the 4th PC had a low Cronbach’s alpha of 0.214 low reliability). The results of the final analysis, which was performed with 11 variables (attributes with loadings below 0.4 were omitted) and 3 dimensions, are displayed (Table 4.24).

Table 4.24. Principal component loadings of field characteristics based on CATPCA analysis using variable principal normalization

Variable	Dimension			Total
	1	2	3	
Pure stand cropping	**0.724**			0.538
Mixed cropping	**-0.635**			0.435
Agroforestry	**-0.633**			0.529
Minimum tillage	**-0.435**			0.373
Fallowing	**0.478**			0.408
Residue incorporation	**-0.646**			0.538
Quantity of fertilizer (planting)		**0.74**		0.713
Fertilizer quantity (top dress)		**0.732**		0.717
Residue composted			**0.623**	0.528
Residue used as fodder			**-0.696**	0.657
Residue used as fuel			**-0.464**	0.387
% of Variance	**23.951**	**15.765**	**13.219**	**52.936**
Cronbach's Alpha	**0.682**	**0.466**	**0.344**	**.911[a]**

a. Total Cronbach's Alpha is based on the total Eigenvalue.

About 53% of variability in farm management was explained by the first 3 PCs. PC 1 was correlated positively with pure stand cropping and fallowing, and negatively with mixed cropping, agroforestry and minimum tillage. PC 2 was associated with fertilizer usage rates both at planting and top dressing. The third component was related to residue compositing (positive) and residue use for fodder and fuel (both negative).

Visualization of the relationships among the farm characteristics, is presented (Figure 4.20).

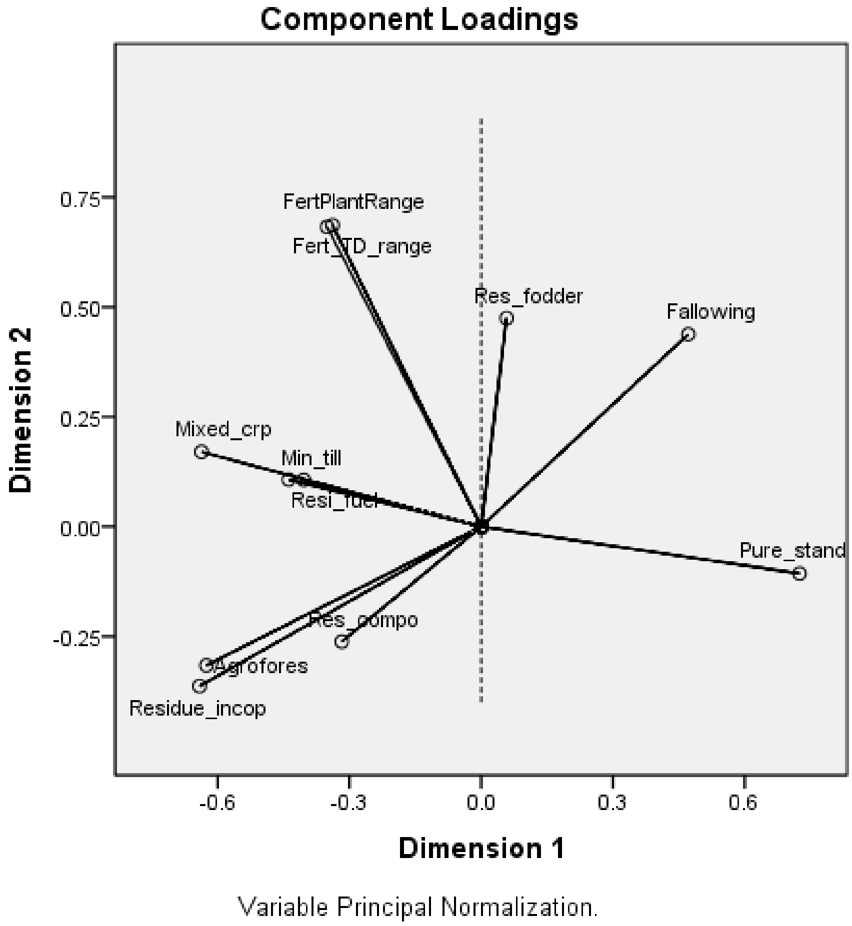

Figure 4.20. Correlation biplot showing the relationship between farm variables.

The relationships between farm practices which are represented by their correlations with their PCs are shown by vectors pointing towards the category with the highest score. The length of the vectors reflects the influence of the variables in relation to variation in farm management practices. Fertilizer application rate and pure stand cropping were highly influential in PC 1 and PC 2, respectively. The small angle between fertilizer application rate during planting and growth, reflects a strong positive correlation between the two variables. On the other hand, a large angle (approximately 180 degrees) between pure stand and mixed cropping shows a strong negative correlation. Figure 4.20 suggests that a priori four classes of field management practices can be identified across the studied farming households.

4.1.4.2.3 Correlations among soil properties

Variables of soil characteristics were distributed into three components through FA (Table 4.25). Factors were extracted using PCA and Varimax rotation with Kaiser Normalization.

Based on the eigenvalues threshold of >1, five components met the criteria. However, some components had either low loadings (<0.4) for all the variables or had significantly high loadings for the same variable across multiple components (multicollinearity). A three-component solution accounting for 70% variance was the best compromise. Similarly, the resulting Kaiser-Meyer-Olkin (KMO) value of 0.5 justifies the sampling adequacy of the sample. Bartlett's test of spherity was significant (<0.00001) suggesting correlation between the variables albeit with multicollinearity possibility (Finch, 2013).

Table 4.25. Principal component loadings of soil variables based on CATPCA analysis using variable principal normalization

Rotated Component Matrix[a]

	Component			
Variable	**1**	**2**	**3**	**Communalities**
K (Exchangeable)	-.812			.786
Na(Exchangeable)	.877			.855
CEC	.673			.697
AL-P2O5	-.770			.821
AL-K2O	.965			.937
pH.H2O	-.443			.239
Mg (Exchangeable)		.921		.890
Ca(Exchangeable)		.736		.623
Base saturation		.927		.899
Sand			.857	.848
SOC			-.455	.222
Ava.N			.643	.624
Eigenvalues	3.799	2.962	1.681	
% of Variance	31.657	24.685	14.006	
Cumulative %	31.657	56.342	70.348	

PC1, was associated with exchangeable K (negative), Na (positive), CEC (positive), extractable P (negative) and K2O5 (positive) and pH (negative). PC2 was described by exchangeable cations (Mg and Ca) and base saturation. PC3 dimension was defined by sand and available N (positive), and SOC (negative). Two-dimensional component loading plots, visualizing the relationships among the soil attributes are presented in Figure 4.21.

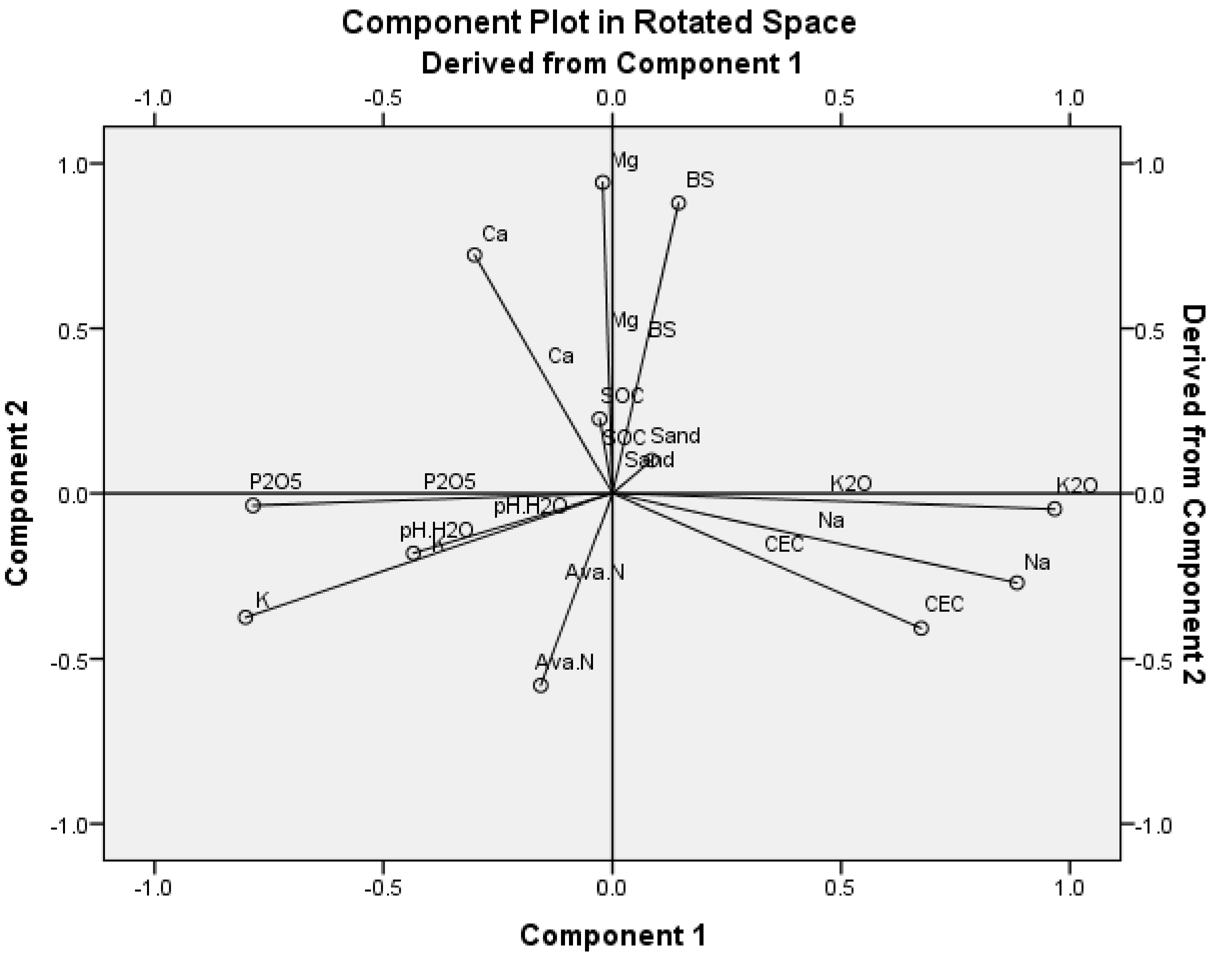

Figure 4.21. Plots of component loadings obtained from factor analysis describing the relationships among soil properties

As shown by the length of the vectors, extractable P, base saturation, exchangeable Mg and Na were highly influential in the variation of soil properties. Available P correlated negatively with extractable P. Mg, Ca and BS were strongly positively correlated.

4.1.4.2.4 Farm typologies based on clustering

Farm typology is the systematic classification of farms into groups that have common characteristics, using several methods, including multivariate methods. Ideally, farm types should reflect the potential access of different households to resources for managing their soils (Makate et al., 2018).

Soil variables with the highest loading as revealed by PCA were selected for inclusion in the cluster analysis. Non-hierarchical Two-step clustering approach was used. Two clusters were automatically determined based on Bayesian Information Criterion (BIC). However, upon close examination of the retained clusters with respect to the field observations (Goswami et al., 2014), the classification was not very meaningful. The solution was repeated with 3 clusters which seemed representative of the farm households in the study sites (Figure 4.22).

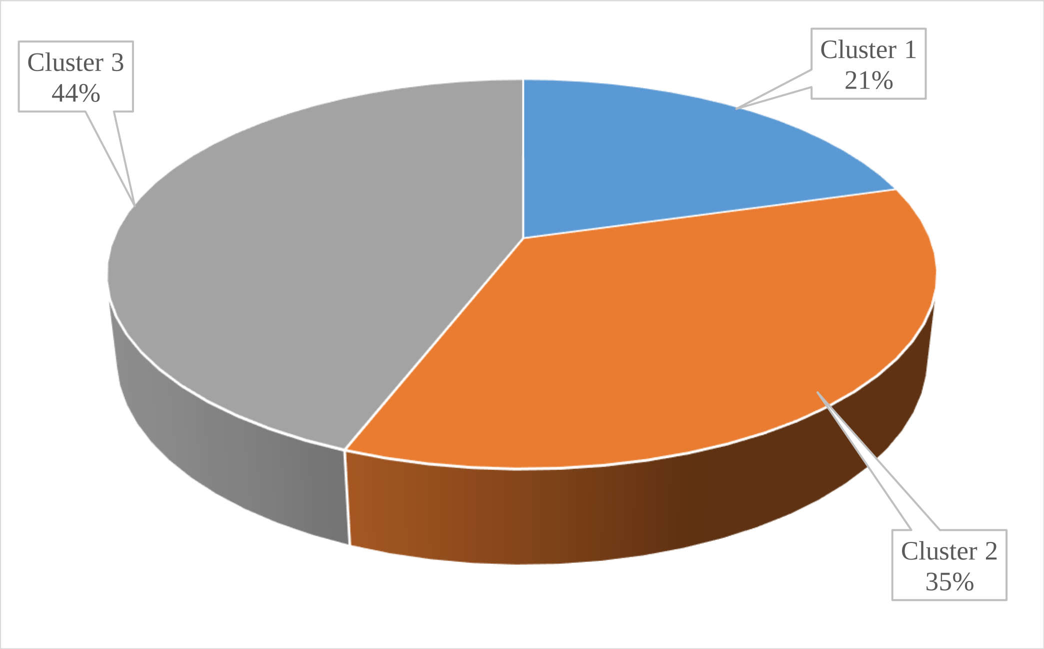

Figure 4.22. Farm household's membership across the clusters

Cluster membership was 14 (20.6%), 24 (35.3%) and 30 (44.1%) households for clusters 1, 2 and 3, respectively. The size ratio between the smallest and largest cluster was 2.14 (a fairly commendable ratio). The overall silhouette measure of cluster cohesion and separation value was 0.5, indicating a fair assignment of data points to cluster centres (Jain & Koronios, 2008). The final clusters obtained were profiled and assigned names: Farm type (FT) 1, 2 and 3.

Figure 4.23 shows household cluster membership across the study sites. Cluster 3 membership is more concentrated close to the slopes of Mount Kenya (Eastern parts of the survey area). Cluster 2 farms seem to be evenly distributed within the study area while cluster 1 fields are more spread towards the east (lower slopes).

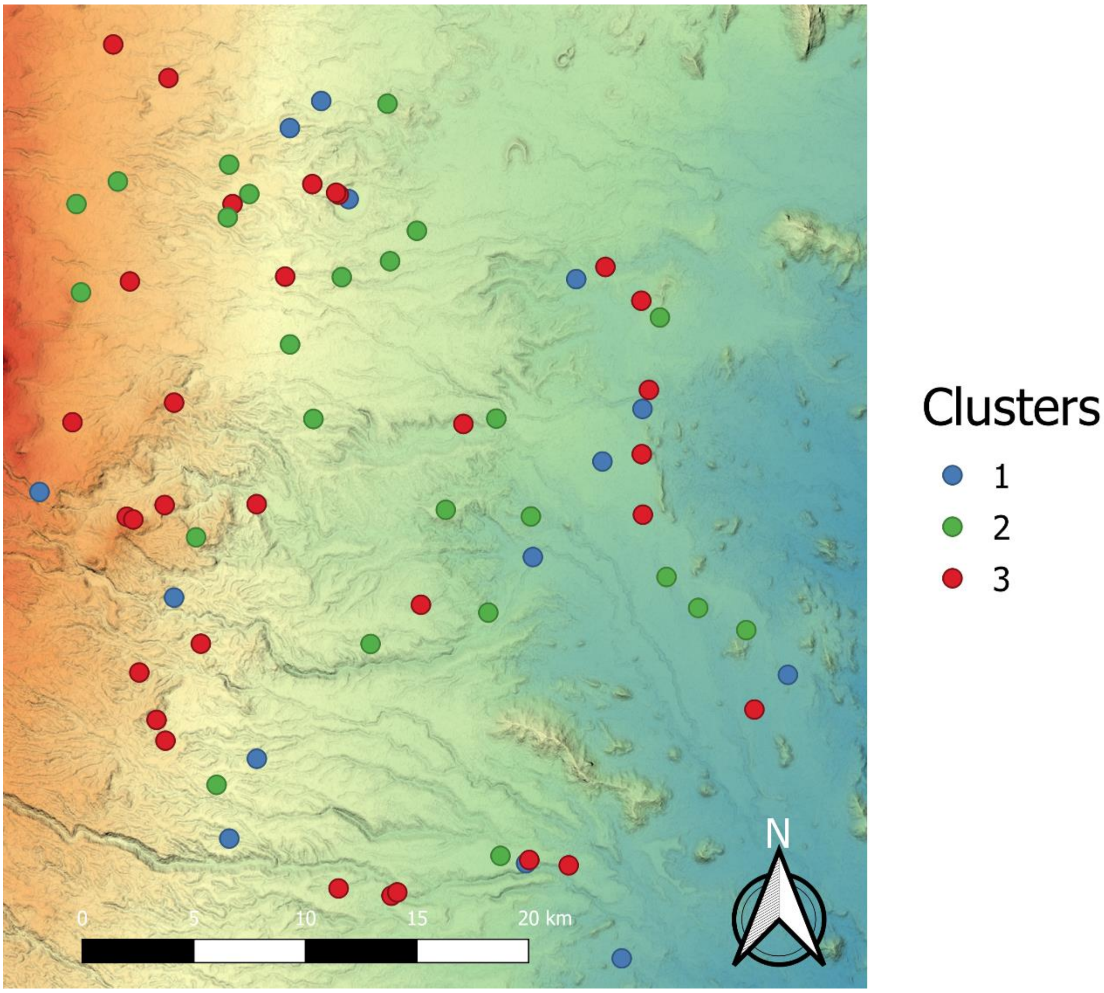

Figure 4.23. Distribution of cluster membership in the study area

Fisher's Exact Test (and Pearson Chi-square where applicable) and one-way ANOVA were conducted for each group of variables to determine factors that were significant in discriminating between the 3 clusters (farm types).

Tendencies of soil properties across Farm Types

Differences in soil properties between clusters were compared based on cluster membership variable, using one-way ANOVA, and results presented in Table 4.26.

Table 4.26. Characterization of identified farm types based on p-value of one-way analysis of variance (equality of mean) of soil properties.

	Cluster (Farm types)			Total	F	Sig.
Variable	**1 (n=14)**	**2 (n=24)**	**3 (n=30)**			
Exch.K	0.388b	1.000a	1.000a	0.874	168.183	0.000
Exch.Mg	0.512b	0.958a	0.733ab	0.767	4.995	0.010
Exch. Na	0.059a	0.000b	0.000b	0.013	26.188	0.000
CEC	16.448a	8.167b	8.033b	9.813	65.407	0.000
BS%.	18.730	19.083	15.633	17.488	2.074	0.132

Sand	27.857	27.958	23.333	25.897	2.159	0.124
AL-P2O5	5.286c	828.717a	740.510b	620.272	348.851	0.000
AL-K2O	195.357 a	13.125b	9.233b	48.926	42.199	0.000
pH.H2O	4.879b	5.083b	6.103a	5.491	38.743	0.000
SOC	0.543bc	1.398a	0.835b	0.974	22.797	0.000
SQI	4.286b	5.291a	5.233a	5.059	3.468	0.037

Each letter denotes a subset of Cluster Number means whose column proportions do not differ significantly (p<0.05). SQI=soil quality index, calculated by summing up assigned threshold values for key selected soil variables for each field (see Amacher et al., 2007)

The distribution of clusters was strongly significant ($p<0.05$) across all the selected soil parameters except for base saturation and sand particle composition, which were weakly significant ($p<0.1$).

Cluster 1 farms have low exchangeable bases (K and Mg), available P, pH, and SOC. These farms have higher values for CEC, extractable K and Na^+ concentration. Cluster 2 farms are characterized by higher exch. Mg, available P and SOC. Farms in cluster 3 have higher concentration of exch. K and pH values. Overall, Fields within farm type 2 and 3 were more fertile that those in farm type 1 as indicated by the SQI. Clay-sand ratio was higher in FT3 than in FT2. Farms in FT2 exhibited higher Base saturation and exchangeable Ca concentration compared to FT3.

Patterns of farm characteristics across farm types

Farm management practices were correlated against the clusters, and results presented (Table 4.27). Farm characterization based on farm management characteristics differed significantly across the three principal components: PC1 (mode of cropping), PC2 (intensity of fertilizer application) and PC3 (utilization of organic resources). Specifically, farm types were significantly different across fallowing practices ($p<0.05$), the intensity of fertilizer application ($p<0.05$) and utilization of crop residue for fuel ($p<0.1$). Proportionally, more farmers in cluster 2 practiced fallowing. Cluster 3 farms exhibited higher fertilizer application rates for both planting and top-dressing, while cluster 2 consists of farms with modest fertilizer consumption. A higher proportion of farmers in cluster 3 used crop residues as fuel.

Table 4.27. Frequency distribution of farm management characteristics across clusters (farm types) in Upper Eastern Kenya.

Variable		**Cluster (Farm types)**						**Total**	**P-value**
		1 (n=14)		**2 (n=24)**		**3(n= 30)**			
		freq	**%**	**freq**	**%**	**freq**	**%**		
Pure stand	No	9a	64.3	14a	58.3	21^a	70.0	44	0.606

	Yes	5a	35.7	10a	41.7	9a	30.0	24	
Mixed cropping	No	3a	21.4	11a	45.8	10a	33.3	24	0.308
	Yes	11a	78.6	13a	54.2	20a	66.7	44	
Agroforestry	No	10a	71.4	18a	75.0	16a	53.3	44	0.255
	Yes	4a	28.6	6a	25.0	14a	46.7	24	
Intercropping	No	12a	85.7	21a	87.5	28a	93.3	61	0.667
	Yes	2a	14.3	3a	12.5	2a	6.7	7	
Residue application	No	2a	14.3	5a	20.8	6a	20.0	13	
	Yes	12a	85.7	19a	79.2	24a	80.0	55	0.856
Fallowing	No	8ab	57.1	13b	54.2	24a	80.0	45	**0.05**
	Yes	6ab	42.9	11b	45.8	6a	20.0	23	
Residue incorporation	No	6a	42.9	15a	62.5	17a	56.7	38	0.538
	Yes	8a	57.1	9a	37.5	13a	43.3	30	
Fertilizer Planting rate	Low	7a	50.0	6a	25.0	7a	23.3	20	**0.043**
	Moderate	1ab	7.1	4b	16.7	0a	0.0	5	
	High	6a	42.9	14ab	58.3	23b	76.7	43	
Fertilizer top dressing rate	Low	7a	50.0	6a	25.0	7a	23.3	20	**0.043**
	Moderate	1ab	7.1	4b	16.7	0a	0.0	5	
	High	6a	42.9	14ab	58.3	23b	76.7	43	
Residue composting	No	13a	92.9	19a	79.2	23a	76.7	55	0.526
	Yes	1a	7.1	5a	20.8	7a	23.3	13	
Residue for fodder	No	2a	14.3	5a	20.8	5a	16.7	12	0.921
	Yes	12a	85.7	19a	79.2	25a	83.3	56	
Residue for fuel	No	9ab	64.3	18b	75.0	14a	46.7	41	**0.11**
	Yes	5ab	35.7	6b	25.0	16a	53.3	27	

Each letter denotes a subset of TwoStep Cluster Number categories whose column proportions do not differ significantly (p<0.05). Fertilizer application rates: low= less than 25kg, moderate =25-50kg, High= >50kg/acre.

Noticeably, cluster 1 farms are associated with mixed cropping, intercropping and residue incorporation. Fertilizer application intensity is low, and farmers were very unlikely to compost crop residues. Farms in cluster 2 have proportionally high cases of fallowing and pure stand cropping, with modest fertilizer application rates, and composting of crop residues. Cluster 3 farms are characterised with high fertilizer application, high propensity to agroforestry and compositing of crop residues.

Socio-economic characteristics across the farm types

Households' socio-economic variables were correlated with the identified farm types and results presented in Table 4.28and Table 4.29. The distribution of farm types in relation to household socio-economic characteristics differed significantly across PC2 (personal attributes) and PC3 (farm size and other wealth indicators). Specifically, farm size, household income, family size and livestock volume were important in delineating farm types. Cluster 3 has averagely larger farms compared to clusters 1 and 2. There is slight farm type differentiation across household income ($p<0.1$). Farms in cluster 1 had lower average income, while cluster 3 had highest income.

Proportionally, majority of households within farm type 1 were male-headed, younger, educated beyond secondary school level and with smaller family size. Cluster 3 farms were characterized by larger family size, higher workforce, and larger livestock units. Cluster 2 farms consisted of mainly older female household heads with medium family size, farm size and income.

Farming was the primary occupation for household heads in farm type 1, who had a higher education level, and income compared to their counterparts in farm type 2. Comparatively, farms in cluster one had higher access to soil testing services and financial (credit) information. Members of farm type 2 had a higher access to animal husbandry information, larger farm size, livestock and more family members working on the farm.

Table 4.28. Characterization of identified farm types based on p-value of one-way analysis of variance (equality of mean) of socio-economic characteristics.

Variable	Cluster	N	Mean	Std. Dev	Min	Max	F	Sig.
Family size	1	14	4.714	1.326	3	7	0.958	0.389
	2	24	5.125	1.676	1	8		
	3	30	5.433	1.695	2	11		
	Total	**68**	**5.176**	**1.62**	**1**	**11**		
Farm size	1	14	2.482bc	2.202	0.25	6	3.692	0.03
	2	24	2.813b	2.329	0.25	10		
	3	30	4.598a	3.512	0.5	10		
	Total	**68**	**3.532**	**3.011**	**0.25**	**10**		
TLU	1	14	1.565	1.083	0.62	4.85	1.497	0.232
	2	24	1.455	1.259	0	5.2		
	3	30	2.133	1.845	0	7.07		
	Total	**68**	**1.777**	**1.532**	**0**	**7.07**		
Workforce	1	14	3.071	1.385	1	5	0.862	0.427
	2	24	2.667	1.494	1	6		
	3	30	3.167	1.392	1	6		
	Total	**68**	**2.971**	**1.424**	**1**	**6**		
Age	1	14	41.071	17.022	20	73	1.617	0.206
	2	24	49.125	12.081	26	75		

Variable	Cluster	N	Mean	Std. Dev	Min	Max	F	Sig.
	3	30	47.867	13.627	30	74		
	Total	**68**	**46.912**	**14**	**20**	**75**		

Table 4.29. Comparison of households' socioeconomic characteristics across the identified farm types in upper Eastern Kenya

Variable	Category	Farm type (Cluster)						Total	%	Coeff	Sig
		1 (n=14)		2 (n=24)		3(n=30)					
		Freq	%	Freq	%	Freq	%				
Gender	Female	5	35.7	11	45.8	12	40	28	41	0.077	0.855
	Male	9	64.3	13	54.2	18	60	40	59		
Income (Ksh, '000)	<75	7	53.8	10	52.6	11	42.3	28	48.3		**0.13**
	75-150	1	7.7	4	21.1	6	23.1	11	19		
	150-225	5	38.5	4	21.1	3	11.5	12	20.7		
	>225	0	0	1	5.3	6	23.1	7	12.1		
Education	Primary & below	5	35.7	14	58.3	19	63.3	38	56	0.207	0.218
	High sc.& above	9	64.3	10	41.7	11	36.7	30	44		
Farm occupation	No	1	7.1	2	8.3	2	6.7	5	7	0.029	0.973
	Yes	13	92.9	22	91.7	28	93.3	63	93		
Farming experience	<20	7	50	8	33.3	16	53.3	31	46	0.18	0.318
	>20	7	50	16	66.7	14	46.7	37	54		
Ext Contact	No	10	71.4	13	54.2	19	63.3	42	62	0.13	0.557
	Yes	4	28.6	11	45.8	11	36.7	26	38		
Soil info	No	13	92.9	22	91.7	26	86.7	61	90	0.09	0.759
	Yes	1	7.1	2	8.3	4	13.3	7	10		
Siol TEST	No	12	85.7	8	33.3	26	86.7	46	68	0.141	0.5
	Yes	2	14.3	6	25	4	13.3	12	18		
Credit INFO	No	14	100	21	87.5	28	93.3	63	93	0.172	0.356
	Yes	0	0	3	12.5	2	6.7	5	7		
Crop Husbandry	No	12	85.7	20	83.3	24	80	56	82	0.059	0.887
	Yes	2	14.3	4	16.7	6	20	12	18		
Animal husbandry	No	14	100	21	87.5	24	80	59	87	0.216	0.188
	Yes	0	0	3	12.5	6	20	9	13		
Agribiz	No	14	100	24	100	29	96.7	67	99	0.136	0.526
	Yes	0	0	0	0	1	3.3	1	1		

4.2 Discussion

4.2.1 Soil characterization and classification

4.2.1.1 Soil properties and soil fertility.

The analysed properties include the available Nitrogen (N), phosphorus (P), extractable and exchangeable potassium (K), soil organic carbon (OC), pH, Calcium (Ca), Magnesium (Mg). The generally low R^2 values of the individual soil properties predictions demonstrate the difficulty of obtaining reliable field-specific estimates, particularly when the within-field variation in the measured characteristics is low.The overall mean soil pH in the study area was 5.4 (strongly acid) with the lowest pH of 3.9 (extremely acid) and a high of 7.0 (neutral). Soils classified as fertile by farmers had a mean pH of 5.7 (medium acid) while the infertile soils had a pH of 5.1 (strongly acid). Spatial variations in soil properties are anticipated due variations in landscape (topography, relief), geology (parent materials) and climate (Muchena & Gachene, 1988b). The topography of the area displays significant terrain diversity (ranging from 300 to 5,199 m), resulting in extremely varied climatic conditions including precipitation (300-2,500 mm, and decreases from the west to east) and temperature (8°C to 32°C). The study area consists of a variety of rocks ranging from teriary volcanics to unconsolidated sediments. These topographic, geological and climatic diversity result in the formation of a wide range of soils (Wanjogu et al., 2001).

The strongly acid nature of most of the soils in the area is attributed to strong weathering and leaching, especially in the lower regions. The avilability of plant nutrients is highly determined by pH, and tend to be optimal for most agricultural crops (such as maize) within the neutral range of 6.0 to 7.0 value (Oshunsanya, 2019), with the exception of equally essential micronutrients including iron, zinc, manganese and copper which are readily available at pH 5.5 and below. However, too acidic soil hinders root growth and copper may become too toxic (Wanjogu et al., 2001).

The average SOC in the study area for topsoil (0-20 cm) was 1.34% with a range of 0.5%-5.9%. Farms in uplands had generally higher SOC (1.6) than lowland fields. The amount of SOC is positively correlated to elevation. The accumulation of SOC in highland areas varies greatly due to diverse environmental conditions (Arunrat et al., 2020). There was more SOC in fertile soils (1.6) compared to infertile soils (1.1).

The mean OC for fertile soils falls within a moderate range while the mean for infertile soil falls under the description of low SOC levels. Thus, farmers' judgement of fertile soil meets the scientific estimates, based on SOC attribute. About 23% of the sampled farms had low OC (=< 1.2%). These values are interpreted following the rating documented by Wanjogu et al. (2001). The low levels of SOC can be explained by farming practices. Farms that practised agroforestry, manure application and minimum tillage had significantly higher levels of SOC. farms with tea plantations had higher proportions (moderate) of SOC, followed by maize farms. Plots with legumes had low SOC. This can be attributed to preferential treatments given to certain crops based on the importance attached to them by the farmers, and which determines amount of fertilizer and manure applied to the crops. That, farms classified as fertile had higher fertilizer application rates during plant as well as split application during growth, is thus not surprising. Topological attributes and climatic factors temperature and altitude) can also influence SOC content (Willy et al., 2019). The higher levels of OC in the Northern and Eastern parts of the study area, can be attributed to its location in high altitude zone with cooler climates. Interestingly, sloping farms (10-30%) had higher SOC. This unexpected observation could have been influenced by land use and management practices (Moges et al., 2008). A study by Sainepo et al. (2018) reported higher OC in shrublands than grasslands and bare lands. Patterns of SOC in Kenya suggest high levels of organic matter in the highland soils (Bindraban et al., 2018). Low SOC that characterizes tropical regions has been alluded to the high rate of soil oxidation (Omenda et al., 2019) and continuous cropping (Bindraban et al., 2018; Muriuki & Kanyanjua, 1995). In this study, continuous cropping was indicated by farmers as among the most important contributors to declining soil fertility. Studies investigating effects of land use change on soil fertility have shown significant decline in OC and other elements (including TN, Exch. Mg and Ca) when previously fallowed or forested lands are cultivated (Willy et al., 2019).

Total Nitrogen (TN)

The overall mean TN was 24.5 mg/kg with a range of 6-114mg/kg. As expected, fields in the upland had a slightly higher mean (24.8) compared to lowlands. This could be attributed to leaching (because of low pH) and the effect of deposition of coarser sediments from erosion activities (Moges et al., 2008). Nitrogen and other plant nutrients tend to be deficient in strongly acid soil (Wanjogu et al., 2001).There were no significant differences in TN between farmer-described fertile and infertile soils. However, TN was influenced by various farm management practices including type of farming, mulching and land use (crop type). Mixed Crop-livestock farming systems had higher TN levels compared to farms which practiced only crop farming. TN was higher on farms that practised mulching. Tea plantations had the highest TN content (46.3). More than 65% of the farms sampled failed to meet the 20g/kg TN threshold based on Loveland and Webb assessment (2003) or 0.2% (Horneck et al., 2011; Willy et al., 2019). This proportion is however lower compared to the findings by Mutuma (2017) which suggest that more than 93% of the farms were below the TN threshold value. This improvement could be attributed to better farm management practices being adopted by farmers. Based on the study locations, more farms (70%) in the lowland (Tharaka Nithi) fell below the 20g/kg TN threshold level compared to 64% in the uplands (Meru). These differences could be explained by variations in management practices across the two counties. For instance, results indicate that Meru had higher fertilizer application rates both planting (41.5kg) and during crop growth (53kg). On the other hand, the application rates in Tharaka Nithi during planting and top dressing were 16kg and 45kg per acre respectively. The generally low TN levels could also be attributed to continuous cropping and limited use of both mineral and organic fertilizer. Removal of crop residues from the farm after crop harvest significantly contributes to the decline in Nitrogen. Results indicate that 86% of farmers use crop residues as animal fodder and only 34% of farmers retained crop residues for incorporation into the soil. This finding confirms the long-held view that suggests nutrient depletion as one of the most important causes of soil fertility decline among the farming systems in sub Saharan Africa. Nitrogen and other nutrients are removed from the soil through crop harvesting with little replenishing efforts amounting to nutrient mining (Chianu et al., 2012). Mixed crop-livestock enterprise presents a symbiotic relationship between crop farming and livestock production. Livestock compensate for the offtake of crop residues from the farm, by supplying manure that plays a vital role in enhancing soil fertility. However, both enterprises are responsible for depletion of mineral nutrients due to their contribution to removal of nutrients contained in the produce sold. Livestock operations can interrupt the cycling of nutrients in the soil leading to depletion due to overgrazing or when they are sold off without replacement (Karr, 2003). Application of nitrogen fertilizer is critical in replenishing the extracted amount of nitrogen (Willy et al., 2019) and to maintain soil productivity and to sustain high yields (Bindraban et al., 2018). However, the right type of fertilizer should be used while avoiding overfertilization with certain nutrient elements which are likely to create deficiencies in the supply of other essential nutrients (Karr, 2003). Availability of nitrogen is influenced by soil pH, and thus acidic soils are low in N.

Variation of nutrient elements across fertile and infertile soils

Following the assessments suggested by Bindraban e. al. (2018), more than 60% of the farms had below the recommended optimum P range of 16-20 for top soil samples (0-20 cm), with 38.5% having very low P level (0-8). These results are consistent with the findings of Bekunda et al (2005) investigation of soil fertility status which showed low phosphorus level in 64% of the farms in East Africa. More than a quarter of the farms (28.6%) have low extractable potassium, below the optimum range of 9-15.Generally, most farms had adequate levels of potassium within the topsoils. This could be attributed to increasing responses of the various crops to K fertilizers (Bekunda et al., 2005)

Many studies have flagged mineral nutrient loss as one of the major reasons for the underperformance of agriculture in sub Saharan Africa (Giller et.al, 2009; Jayne et al., 2010).. This trend has been attributed to continuous cultivation leading to nutrient mining without effective replenishment regimes (Bindraban et al., 2018). Optimization of farm productivity in many cases, has hardly been accompanied by corresponding increased investment in mineral nutrients replenishment through adequate fertilization (Karr, 2003). Similarly, sub-optimal management practices, that can largely be alluded to the lack of adequate management expertise, significantly contribute to soil mineral nutrient depletion (Hengl et al., 2017; Karr, 2003). Indeed, most of the farming systems in SSA region suffer from severe nutrient depletion due to the traditional nature of the farming methods that are characterized by low use of fertilizers (Chianu et al., 2012) and continuous cultivation (Mugendi et al., 2007).

Nutrient deficiency in the tropics has equally been facilitated by the nature of soil and climate. A significant proportion of soils in Kenya are highly weathered and thus have low nutrient reserves including limited capacity to supply such important elements as potassium, phosphorus, calcium and magnesium (Bekunda et al., 2005). The availability of these soil nutrients is strongly determined by soil pH. Soils in the study area are strongly acidic with a mean pH value of 5.4. Such soils need to be neutralized by addition of lime (Bindraban et al., 2018). Nitrogen deficiency is also explained by the low level of SOC as established by this study.

4.2.1.2 Soil classification and Reference soil groups (RSGs)

A total of eight reference soil groups were identified during soil classification of the 69 profiles, namely Nitisols (35), Acrisols (17), Cambisols (6), Leptosols (3), Andosols (2), Gleysols (2), Plinthosols (2) and Umbrisols (2).

The diagnostic horizons used in defining respective reference soil groups include, argic and nitic horizons (Nitisols), Argic horizon (Acrisols), andic horizon (Andosols), Cambic horizon (Cambisols), Pisoplinthic horizon (Plinthosols), Leptosols were diagnosed by Umbric horizon and continuous rock. Gleysols were characterized by argic, umbric and Nitic horizons. Umbrisols were diagnosed by argic and umbric horizons.

Nitisols and Acrisols are the most dominant Reference soil groups in areas around Mount Kenya. The results of this study indicate predominance of Nitisols in the highlands, while Acrisols were common in the lowlands (Figure 4.4). The general pattern of the soil resources is greatly influenced by climate, physiography and parent material (Speck, 1982). The areas in the upper highland receive higher rainfal of up to 2,500 mm of rainfall annually compared to lowland areas which experience up to 2,200 mm of rainfall in a year (County Government of Tharaka-Nithi, 2013; Meru County Government, 2014).

Acric Dystric Nitisol (Andic, Aric, Ochric) was the most widespread type of Nitisols. The Acric Argic horizon implies that this type of Nitisol is characterized by low base saturation (<50%) and CEC (<24 cmol kg^{-1})(IUSS Working Group WRB, 2015), supporting a consistent argument that most of the soils in the country are low activity clays and suffer from low BS. The soils classified as Nitisols were strongly acid, with a mean pH value of 5.3 with a minimum of 3.7, and low extractable P (11.3 mg kg^{-1}). These findings are consistent with Muindi et al's (2017) who found Nitisols to be extremely acidic, ranging between 3.7-4.5 and with low available P (<15 mg kg^{-1}).The suggested pH for the availability of most of the plant nutrients is 5.5-7.0 (Okalebo et al., 2002). The low pH explains the low BS tendency and hinders availability of adequate P for plant uptake. The high acidity of the Nitisols is attributed to Phosphorus deficiency, aluminium toxicity, high proportion of Al saturation and low exchangeable bases (Muindi et al., 2017). The exchangeable-K, Mg, Ca had a mean of 0.8 cmol kg^{-1}(low), 0.6 cmol kg^{-1} (medium) and 1.8 cmol kg^{-1} (very low) respectively.

Appropriate soil management practices should address the efficient utilization of phosphorus fertilizer and include application of P fertilizers in such forms as slow-release, low-grade phosphate rock (Muindi et al., 2017; NAAIAP, 2014). Because of high P-sorbing capacity, Nitisols (of the highlands) only respond to larger rates of phosphate (Okalebo et al., 2002).

Acrisols were the predominant soils in Tharaka Nithi region. Dystric Acrisol (Cutanic) was the most prevalent type of Acrisol. These soils are strongly weathered with low base saturation (<50%) and low activity clays (CEC<24 cmol kg^{-1}), thus giving a pointer to low soil fertility.

CEC is determined by clay texture and amount of OM in the soil. Generally, fertile soils have a CEC of > 24 cmol kg^{-1} while those with less than 16 cmol kg^{-1} are considered infertile (Gachene & Kimaru, 2003). On the other hand, an A umbric horizon (which was rare and only evidenced by one profile), suggests rich humic substances (Jaetzold & Schmidt, 1983). The B-horizon (argic) of Acrisols is characterized by illuviation of clay minerals, thus resulting in significant textural variations over relatively short distances. The Acrisols were mainly loam (84.3%) and clay (15.7%), and dominated by clay loam (58.8), and silt clay loam (21.6%) USSD textural classes. The clay content varied significantly between the topsoil and subsoil ($p<0.05$), with higher clay proportion in the subsoil due to pedogenetic processes (IUSS Working Group WRB, 2015). The impervious subsoil of the Acrisols restricts roots penetration , and as such these soils have poor water storage capacity (Muchena & Gachene, 1988b). Limited rootable depth has largely been acknowledged as a critical constraint to soil fertility and crop performance (Bindraban et al., 2018).

The analysis of soil attributes of Acrisols suggest low exchangeable bases due to leaching and extensive weathering (IUSS Working Group WRB, 2015). Leaching results in the movement of nutrients from topsoil to the lower horizon (Problems related to soil structure)The mean for exchangeable K, Mg and Ca were 0.8 cmol kg^{-1} (low), 0.7 (medium) and 2.1 cmol kg^{-1} (very low), respectively. Soil mineral nutrients were moderate for available N (15 mg kg^{-1}), Available P was (11 mg kg^{-1}), Soluble K was very high (>800 mg kg^{-1}). Soil OC was low (<1.5). Soil pH was strongly acid (5.5) due to weathering of acid rocks and degradation (IUSS Working Group WRB, 2015).

Soil properties of Reference soil groups compared with recommended thresholds.

Results suggest that soils in the study area are characterized by low pH (acidity), low organic carbon, low exchangeable bases, and inadequate plant minerals. Replenishing of the removed nutrients (through crop harvest and other processes including leaching and vaporization) through regular applications of both organic and inorganic inputs, is critical. Relating of soil quality indicator thresholds against soil properties for each reference soil group indicate significant soil fertility inadequacies across the soil types.

In terms of mineral nutrients, available N was low in 35.7% of Acrisols, 40% of Cambisols, 20% o Nitisols and 50% of Umbrisols. Available P was low in 68.6% of Acrisols, 33.3% of Andosols, 77.8% of Cambisols, 75% of Leptosols, 81.7% of Nitisols, 80% of Plinthosols and 33.3% of Umbrisols. Extractable K was generally high in all the soils.

Exchangeable bases were significantly low across the reference soil groups. Ca was very low (<5.5 cmol kg^{-1}) in all the soils. Acrisols had moderate (0.4-0.8 cmol kg^{-1}) Mg content (68%), 50% of Andosols and 16.7% of Cambisols had low Mg (0.2-0.4 cmol kg^{-1}). Nitisols, Leptosols, Plinthosols, Umbrisols and Gleysols had moderate Mg. Exchangeable K was low across all the reference soil groups.

Soil OC was low (<1.5%) in 68% of Acrisols, 83.3% of Andosols, 76% of Cambisols, and 90.4% of Nitisols.

Soil pH ranged from strongly to extremely acid (5.1-4.5) in 44% of Acrisols, 66.7% of Andosols, 22.2% of Cambisols, 33% of Gleysols, 50% of Leptosols, 64.8% Nitisols, 40% of Plinthosols, and 33.3% of Umbrisols

The implication of the prevailing soil characteristics on farm management have comprehensively been discussed in previous sections.

4.2.2 Soil fertility Management practices

4.2.2.1 Household demographic and socio-economic characteristics

Demographic characteristics indicate that most of the farmers (60%) were aged above 40. This could as well suggest a relatively older farming community, considering that Kenya is generally a youthful country with a median age of 20 years (KNBS, 2019). The scenario concurs with the country's concern that youths are shunning from agriculture and instead opting for formal employment (CIDP, 2018). While the average household in the study area stood at five persons, the mean for members actively involved on the farm was estimated at three persons, affirming farmer's view of labour shortage as reported during interviews.

Results indicate that less than 10% of the farming household heads in Mount Kenya East region had attained higher education level. Literacy has been shown to be a major driver of technology adoption (Mponela et al., 2016). Farmers with ability to read and write are presumed to have higher capacity to capture and synthesize technical information that characterizes some of the ISFM technologies (Marenya & Barrett, 2007). However, access to training from agricultural extension providers can compensate for inadequate formal training through awareness creation training (Mponela et al., 2016). Our results, however, indicate low contact with extension providers and extension-related information packages, including soil testing and training on soil fertility management, crop and livestock husbandry. Lack of financial education and training in agribusiness, could also be a hindrance to farmers participation in production for the market, and thus low adoption of superior technologies (Chianu et al., 2012).

The average household farm size was 1.3 ha. The size of land owned by a household is a major determinant in the adoption of agricultural practices. The general hypothesis is that farmers with large farm size are more likely to invest in farming technologies compared to their counterparts with small farms (Chianu et al., 2012).

About half of the farmers had more than 20 years of farming experience. Studies show that experience in farming is likely to influence farmer's decision to adopt a given technique. Farmers with little or no experience tend to be risk-averse, and will tend to try out on as few techniques as possible (Mponela et al., 2016).

Nearly 54% of the interviewed farmers were male. Gender has been identified by several studies as a key determinant of technology adoption (Chianu et al., 2012; Marenya & Barrett, 2007; Mponela et al., 2016). In a study by Mponela et al. (2016), male farmers were more likely to combine inorganic fertilizers and manure compared to women. This variation could be attributed to differences in accessibility to resources between men and women (Njuki et al., 2008). Our results would suggest equal access to resources across gender.

4.2.2.2 Adoption of SFMP

Fertilizer and manure were used by the highest proportion of households (93.4%). This could be attributed to a number of reasons, including their immediate returns (of course when accompanied with the use of improved seed varieties) (Holden & Mangisoni, 2013). Increased fertilizer uptake is also stimulated by availability of government subsidy programmes (Odhiambo Ochola & Fengying, 2015). However, as observed during the interviews the programme is marred with a myriad of bottlenecks including inefficiency challenges. The distorted subsidy programme (Birch, 2018) and high market fertilizer price (Chianu et al., 2012) among other factors, explain the generally low and irregular application rate (Ariga & Jayne, 2011; Wawire et al., 2020). High use of manure is alluded to the mixed crop-livestock farming system which is practiced by most of the farmers. However, the available manure is inadequate (Nalivata et al., 2017) due to low quantity of livestock (averaged at 2.5 units) owned by households. Farmers in Meru and Tharaka Nithi supplemented on-farm produced manure with local purchases. The manure used is often of poor quality due to poor manure management practices which leads to substantive nutrient loss (Makokha et al., 2001; Ndambi et al., 2019).

The wide adoption of agroforestry is a good illustration of farmers employing a particular practice to address a specific need (Mponela et al., 2016). Meru and Tharaka Nithi have a generally rugged terrain, thus susceptible to soil and land degradation. Agroforestry is one of the most promoted campaigns for sustainable agriculture that can curb soil degradation processes, maintain soil fertility and mitigate the region against declining agricultural production. The practice is also key in preserving the ecosystem (Blaser et al., 2017). According to responses from the interviews, farmers in the study area argued that the falling leaves increased soil organic matter, and tree roots were important in holding the soil together to prevent soil erosion. However, interviews with extension officers indicated that poor-resource farmers resort to lumbering as an alternative source of energy for cooking or timber and charcoal and timber for selling (evident from the widespread of timber yards in the various shopping centres in the region).

Residue application is common practice due to the readily available crop residues upon harvesting. However, farmers are faced with a trade-off dilemma because of the multiple uses of residue including feeding animals (fodder) and as fuel, thus only a small amount of residue is incorporated into the soil which is insufficient in replenishing nutrient outflow (Bekunda et al., 2005). Because of the competing needs for residue, the recorded low cases of residue burn are expected. Nevertheless, burning of crop residues is considered (albeit by few farmers) as not only efficient in field preparation for next cropping, but also helps in preserving field hygiene by controlling the spread of diseases (Bonanomi et al., 2007; Wang et al., 2019). However, burning of residues and vegetation has been shown to decrease microbial biomass carbon (MBC) at least on the surface depth impacting directly on soil microbial biomass by killing the microorganisms. However, the effect of burning depends on the intensity of fire (Wang et al., 2019). In their separate research, Scharenbroch et al. (2012) and Alcañiz et al. (2016) found that in fact, slash burning resulted in about 30% increase in soil total C. However, this depends on the time frame.

A moderate proportion of households employed minimum tillage an important practice meant to minimize soil disturbance and mitigate it from soil erosion. Similarly, some areas in the region are characterized by generally friable and deep soils (Dijkshoorn, 2007), that may not warrant continued tillage. Soil workability has severally been identified as a key soil fertility indicator (Kome et al., 2018).

Fallowing was among the least adopted practice. This is expected due to the increasing demand for land occasioned by a bulging population, and thus almost all the available agricultural land is cultivated throughout the year. Fallowing is critical in rebuilding soil productivity through biomass accumulation and nitrogen fixation (Mponela et al., 2016). The low adoption of fallowing also explains the minimal use of residue burn and slash-no-burn practices, which would only be applicable in fallowed lands with regenerated vegetation. Slashing is a traditional silvicultural practice commonly used for clearing vegetation (for virgin fields) or harvest residues in forest plantations (Wang et al., 2019). Slash-and-no-burn exists among households with relatively large pieces of land, with low labour supply to support seamless cropping.

4.2.2.3 Combination and interrelationships between ISFM practices

Based on the hierarchical clustering dendrogram (Figure 4.15), ISFM techniques were separated into 3 classes, implying that farmers only adopt a subset of technologies due to various reasons, including financial constraints, lack of technical capacity and incompatible social, physical and cultural environment. Preferences for a particular set of technologies can be explained by the intention of the farmer to address a specific soil constraint (Mponela et al., 2016), more so in seriously depleted soils or in areas with prevalent soil erosion. As seen in Figure 4.15, the Euclidean distance between clusters show that residue application and minimum tillage (both in cluster 1) are likely to be adopted by the same group of farmers, demonstrating their complementarity nature. This can be affirmed by the strong positive correlation between the 2 practices (as shown in Table 4.12). Fallowing, residue burn and residue-no-burn were practiced by similar farmers (cluster 2). Vegetation clearing is common in farming systems where land is left fallow for a given period of time. In which case, the farmer may employ either residue burn or slash-no-burn, depending on the availability of labour and technology for land preparation, thus the positive correlation (Table 4.12). Resource-constrained farmers would often opt for residue burn to clear the land. Similar farmers employed a technological set comprising of fertilizer, manure use and agroforestry (cluster 3) as shown by Figure 4.15. Strong positive correlations between these practices affirms their complementarity (Place et al., 2003). Manure and fertilizer are the most common practices (Figure 4.8) due to their near-immediate results of providing plant nutrients within the same season of application. Agroforestry, on the other hand, is critical not only in enhancing soil fertility, but also to protect the soil from erosion and degradation which are the most important threats in the area due to its rugged terrain.

4.2.2.4 Determinants of the use of SFM

Manure use was strongly correlated with on-farm labour and livestock unit at $p<0.01$. The manure used on the farm is largely on-farm sourced, and as such, it is influenced by livestock ownership. This finding corroborate previous studies, e.g. (Shikuku et al., 2017). Transportation and application of manure requires sufficient labour input. Several studies have demonstrated that areas near the homestead have benefited more from manure application(Adimassu et al., 2016; Muthamia et al., 2011; Tittonell et al., 2005), a fact that could be attributed to the amount of labour required. These findings corroborate other empirical studies which have established a positive effect of large family size and economically active population on investment in labour-intensive land management activities (Adimassu et al., 2016; Gebremedhin & Swinton, 2003).

Inorganic fertilizer application was also influenced by family size and on-farm labour. These results are inconsistent with a research by Makokha et al. (2001) which investigated determinants of fertilizer and manure use for maize production in Kenya. In their findings, labour was found to only significantly influence manure application but not fertilizer. The findings of the current study could be attributed to the long distance farmers have to travel to the market centre or the National Cereals and Produce Board (NCPB) centres (government's fertilizer distribution centres). Interviews also showed that farmers' access to fertilizer was hampered by long distance to NCPB centres.

The positive correlation of livestock unit and agroforestry could be explained by the fact that the leaves of some tree species are used as animal fodder especially during dry season. Fodder trees have increasingly served as an important source of livestock feed in various farming systems in Africa and have been used mostly to feed dairy cows in the highlands of Eastern Africa (Franzel et al., 2014). In fact, there have been increasing campaigns among researchers and extension providers, in collaboration with farmers in promoting fodder tree practices in various countries (Franzel et al., 2014).

On-farm labour family size, total annual household income, tropical livestock unit (TLU) and access to crop husbandry information were positively correlated with the implementation of agroforestry (tree retention on the farm). The influence of crop management information could be explained by the training received from agricultural extension providers on the proper farm management practices. The scenario is consistent with a long-held consensus that effective extension services is crucial in improving agricultural productivity through provision of information to farmers that guide them in optimal use of their limited resources (Muyanga &

Jayne, 2006). However, responses from interviews with extension providers and farmers paints a gloomy picture of a deteriorating agency (Muyanga & Jayne, 2006).. On the flip side, the commodity-based extension dealing with the major cash crops (tea and coffee) tend to work well, understandably because these services are obviously motivated by profits (Muyanga & Jayne, 2006).

Minimum tillage was significantly influenced by livestock units and access to soil information. The influence of livestock unit could be explained by the complementarity of manure application and minimum tillage. Farmers implement both practices as a strategy to conserve moisture and minimize loss of nutrients (Mponela et al., 2016) protect soil aggregates, reduce soil loss and surface run-off (Turmel et al., 2015). The influence of access to soil information on the implementation of minimum tillage can be attributed to extension activities that include training of farmers on agronomic practices and soil conservation. Agricultural extension providers usually employ an integrated approach encompassing a range of activities (Muyanga & Jayne, 2006).

There was significant positive correlation between contact with extension and fallowing. Fallowing is critical in rebuilding soil productivity through biomass accumulation and nitrogen fixation (Mponela et al., 2016). Surprisingly, our findings did not establish a significant effect of farm size and household size on the decision to implement fallowing as has been demonstrated in previous related research (e.g.Teshome et al., 2016). This can be explained by the fact that fallowing was practiced by a very small proportion of farmers (as such the assumptions for analysis for some analysis models were not satisfied).

Our results indicate that slash-no-burn was practiced mostly by older farmers. This can be attributed to shortage of labour to support seamless cropping, or the relatively short planning horizon of the older household head (Nigussie et al., 2017). The significant negative correlation of age with access to extension and agribusiness information (Table A 1), may imply that young farmers are more likely to seek for extension service and to approach agriculture as a business.

The positive correlation between access to livestock husbandry information and slash-no-burn can be explained by the fact that most of the farmers (with livestock) would usually harvest grass from the uncultivated fields to feed to the animals. During the survey we could observe farmers harvesting grass on the roadsides to supplement livestock feed.

4.2.2.5 Fertilizer and manure use

There is increasing adoption of inorganic and organic inputs as suggested by our results. This finding is consistent with previous studies on adoption of soil fertility management practices in Kenya. For instance a research by Ariga and Jayne (2011) established that the proportion of Kenyan farmers using fertilizer increased from 59% in 1997 to 72% in 2007. However, not every region across the country has experienced similar rise (Marenya & Barrett, 2009). The high potential areas such as Kenya's central highlands and Western Kenya have experienced higher proportion growth of fertilizer users, and are said to use nearly 6 kilograms more fertilizer per acre (Ariga & Jayne, 2011).

However, caution should be exercised in drawing conclusions as the statistics only imply application of fertilizer at least on one plot on the farm and not necessarily on the entire agricultural farm. A study by Crowley and Carter (2000) found that 90% of farmers in Western Kenya used inorganic fertilizers. However, more than 80% of the fields received less than 50% of the recommended 120 kg per ha (Chianu et al., 2012). A study by Chianu et al. (2012) reports that both inorganic fertilizer and organic resources are inadequate among the smallholder farmers across sub-Saharan Africa. A condition that has resulted to fertility gradients within farms. consequently, farmers give preferential treatment to specific crops and plots on the farm (Chianu et al., 2012; Dawoe et al., 2012).

4.2.2.6 Accessibility of fertility resources

Most of the manure used by farmers (84.8%) are generated on the farm and as such it is influenced by aggregated livestock ownership (Tropical Livestock units or TLU). However, a little amount of manure is produced on the farm due to a relatively small amount of livestock (averaged at two TLU) owned by smallholder farmers. The deficiencies are partly filled by purchases from the local market and neighbouring household farms as well as borrowing from kinsmen. The nutrient quality of manure varies widely based on management practices including feed sources, decomposition rate and the handling (Makokha et al., 2001). Scarcity of manure is the major constraint undermining its application, a situation that could be attributed to a limited number of livestock owned by smallholder farmers. Limitation in resource endowment restrains most of the farmers from exploring the option of supplementing farm-produced manure with supplies from the market. The high cost of transporting purchased manure could also hinder farmers from buying organic resources. Unprocessed cattle dung is the most popular type of manure used by farmers. This could be alluded to the fact that technical skills and intensive labour are required in the processing manure resources as suggested earlier by literature.

High proportion of farmers acquire fertilizers by way of direct purchase from the market. This is largely attributed to the liberalization of the fertilizer subsector in the early 1990s which paved way for the entry of the private sector in importation, wholesaling local retailing and distribution of fertilizers (Ariga & Jayne, 2011; Wanzala et al., 2002). However, the fertilizer production-consumption chain has been increasingly been characterized by inefficiencies and high transaction costs leading to fertilizer shortage.

Other options for smallholder farmers' access to fertilizers are through government subsidies and input credit schemes. Fertilizer subsidies are key stimulators of fertilizer uptake and agricultural productivity among low input-low output farming systems. However, only a few farmers accessed fertilizer through subsidized programs. Inefficient administrative processes have been blamed for the poor distribution of subsidized fertilizers, and this has undermined the achievement of the program's objective of increased uptake among the resource-poor farmers. This program has been characterized by a myriad of challenges including delay in availing fertilizers to farmers in time, low quality fertilizer and limiting in major nutrients for specific locations. The distribution process is characterized by misappropriation (KPA, 2017), long bureaucratic application process and long distance to the designated distribution centres, National Cereals Produce Board (NCPB) depots.

The most widely used fertilizers are calcium ammonium nitrate (CAN 26%) and diammonium phosphate (DAP 18-46-0). Increased use of di-ammonium phosphate (DAP) is attributed to its high nutrient value. It should be noted that most of the African countries import their mineral fertilizers, and thus it is cost-effective to import fertilizer with high nutrient content (P and N). However, excessive phosphates can undermine absorption of equally important micronutrients such as iron and zinc thus slowing the growth of crops. Other common fertilizers include complex NPK, Urea and Triple Superphosphate. However, most of these fertilizers are characterized by very dismal quantities of secondary nutrients such as S, Ca and Mg (Bayite-Kasule, 2009; Sanginga & Woomer, 2009). This situation partly explains the negative nutrient imbalance and low productivity that define most of the African farming systems (Chianu et al., 2012). Some of these fertilizers have produced unsatisfactory results raising questions about formulation of the nutrient components and overall quality of these inputs, and agronomic knowledge of the manufacturers (Sanginga & Woomer, 2009). Lack of farmer's guidance on the appropriate fertilizer or reliance on outdated recommendations are partly responsible for poor crop response. Poor fertilizer quality in Africa has also been attributed to adulteration by unscrupulous traders (Chianu et al., 2012).

Smallholder farmers have generally low income to invest in sufficient manure and mineral fertilizers (Makokha et al., 2001) thus have been compelled into adaptive strategies. Our survey findings indicate that less than a quarter of the farmers (20%) regularly use fertilizer every season. A section of farmers opts for use of fertilizers either only during planting or top dressing while others only during the main planting season. These findings confirm inconsistencies in fertilizer consumption that characterize African farming systems.

4.2.2.7 Determinants of fertilizer and manure use

Education, contact with extension and household income had a significant association with the decision to top dress crops with fertilizer. Low farmer literacy is one of the factors that have been linked to low fertilizer uptake by smallholder farmers (Breman et al., 2005). A study by Marenya and Barett (2009) investigating fertilizer use rates among smallholder farmers in Western Kenya established that younger and educated farmers were more likely to use fertilizers.

Farmers' decision to invest in soil fertility management is largely influenced by the household's income. Our findings corroborate previous studies that have investigated adoption of improved farming practices among smallholder farmers (Chianu et al., 2012; Makokha et al., 2001; Odhiambo Ochola & Fengying, 2015). Farmers with more disposable income are likely to invest in fertility management.

Contact with Agricultural extension influenced adoption of fertilizer and manure. Information on fertilizer recommendations, how to apply fertilizers during top dressing, suitable crops and timing of fertilizer application, is likely to influence farmers positively. These findings are consistent with a large number of studies that have demonstrated a relationship between extension and adoption of sound agricultural practices (Jayne & Muyanga, 2012; Makokha et al., 2001). The impact of extension was evident in Malawi where Starter Pack and Target Input programs driven by extension led to significant benefits (Chianu et al., 2012). However, dwindling extension activities continues to hinder application of agricultural research innovations. In some cases, extension messages are not timely as when needed and in certain cases not clear (Makokha et al., 2001). Surveyed farmers during our study expressed that there was minimal visibility of extension workers. The increasing gap between the actual and potential agricultural production has partly been attributed to the deteriorating agricultural extension (Chianu et al., 2012).

Among the major crops, only maize had significant correlations with the various fertilizer treatment regimes. There was no significant association between tea and coffee and the various fertility treatment regimes. This finding however, contradicts the assertion that fertilizer and manure in African farming systems are largely dedicated to cash crops at the expense of cash crops (Makokha et al., 2001) due to anticipated income (Chianu et al., 2012; FAO, 2004) and availability of input credit schemes for the cash crops. However, resource-poor farmers divert some of the fertilizers from the input credit scheme to support the production of food crops and especially maize as it is the staple crop and usually equated to food security.

There was a significant correlation between the perception of lack of soil fertility skills (as a constraint to soil fertility management) and manure use. It is expected that farmers require skills in the preparation of manure. In fact, all factors held constant, individual farmers skills will influence the type of manure availed. A study by Makokha et al (2001) investigating the factors conditioning the use of manure and fertilizer in Kenya established lack of knowledge as one of the constraints to uptake of manure and fertilizers. Farmers' competence or technical skills in using agricultural inputs is critical in reaping the benefits of such inputs (Dorward & Chirwa, 2011).

The perception of poor fertilizers as a constraint to soil fertility was significantly associated with the use of fertilizer for top dressing. Indeed, poor quality fertilizers, believed to be as a result of adulteration (which is prevalent in African countries) discourages farmers from investing in fertilizers. As noted earlier, the vice is common in repackaged fertilizers, whose initial objective was to accommodate the needs of farmers who demand the inputs in small quantities (Chianu et al., 2012).

The decision to use manure was significantly associated with household farm size. A study by Chinangwa et al. (2006) investigating adoption of soil fertility improvement technologies in Malawi registered similar findings. Large farm size encourages farmers to keep more livestock (mostly cattle) which provide manure for farm use. Further, livestock holding size has a significant relationship with the decision to use manure. Farm size was also significantly correlated with the access to subsidized fertilizer (Table A 2). This implies that farmers with larger land size are more likely to access benefit from the government subsidized fertilizer. Contrary to the reported perception by farmers that subsidized fertilizers are mostly accessed by the rich, the findings of this study did not establish a correlation between income and access to subsidized fertilizer (**Error! Reference source not found.**).

4.2.3 Farmers' and scientific soil fertility assessments compared

This study has described local indicators of soil fertility used by farmers to distinguish fertile from infertile soils. Farmer's evaluation of soil fertility were found to be consistent with findings of Kuria et al. (2018) in Rwanda and Mairura et al. (2007) in Kenya, implying that the results of this study are relevant and consistent with farmers' soil quality knowledge in multiple agro-ecosystems, especially sites with common agro-ecological characteristics.

This study found that all descriptive indicators were scored highly in fertile sites compared to infertile sites. Soil colour scored significantly higher in fertile plots, implying that darker soils were regarded to be more fertile. Several studies (Barrios & Trejo, 2003; Corbeels et al., 2000; Dawoe et al., 2012; Yageta et al., 2019) have shown that soil colour is a widely used indicator by farmers to classify soils in many parts of the world. Soil texture and colour were reported to be most salient and defining for local soil classifications, and colour categories were often combined with texture levels in describing different types of soils (Brouwers, 1993). The darker soils have more soil organic matter concentration than lighter soils and a higher soil water-holding capacity (Lima & Brussaard, 2010). Bicalho and Piexoto (2016) reported soil colour characteristics in poor and fertile fields, showing that a decrease in soil organic material is reflected in the colours of the type of soil mineral components present where by the colours of the mineral components tend to show through when organic matter reduces Quartz and kaolinite are white in colour; hematite (red); gibbsite (yellow) while iron oxides in a reduction environment are grey. These colours can show through when soil organic matter declines, thus indicating poor sites. In their study, Wills et al. (2007), concluded that soil colour provided a rapid and useful method of predicting the SOC content in different land use types using Munsell chart parameters. Munsell colour chart is commonly applied to assess soil colour patterns globally. Essentially, these tools are based on qualitative calibration of soil fertility and crop characteristics to assess soil-crop quality aspects.

Most of the farmers expressed that the presence and high population of earthworms in the soil indicated high soil fertility. This is one of the key biological indicators used in evaluating soil health (Bartz et al., 2014; Lima & Brussaard, 2010; Römbke et al., 2007). Lima et al. (2011) showed that higher diversity of earthworms and other pedodiversity were found in darker soils which contained more clay, organic matter and abundant vegetation. In relation to soil workability (tilth), the soils were rated from easy to more difficult tilling soil types. This difference could be attributed to the role of clay, which is sticky, thus excessive clay content renders management of the soil difficult during dry season cultivation. Soil tilth relates to the soil structure, particles aggregation and pore spaces that are responsible for its friability-an attribute that can be associated with biotic factors including microfauna activities, roots and fungal hyphae and their exudates (Lehmann et al., 2020). Desired (medium) soil tilth could also be attributed to reduced tillage frequency, perennial rooting and organic matter (Stoops et al., 2010). While farmers demonstrate a good understanding of soil tilth, it remains a confusing concept among scientists with no clear protocol for measuring (quantifying) it (Karlen, 2011). The lack of an aggregate stability metric in the scientific SQI (Amacher et al., 2007) is therefore not surprising.

In relation to leaf colour, several studies have utilised leaf colour indices and chlorophyll meters to relate the nitrogen status for different types of crops. The International Rice Research Institute(IRRI) has developed a leaf colour chart (LCC) for rice crop management, while Gholizadeh et al. (2017) reported that the Soil Plant Analysis Development (SPAD) chlorophyll meter readings improved yield prediction in rice based on the leaf N contents.

This study classified farms as either fertile or infertile based on the averages of the sum rankings of individual indicators, thus generating the farmer-descriptive SQI. The findings suggest a general relationship between measured soil quality parameters and farmer assigned score values, which can allow for the integration of farmer soil quality knowledge with scientific assessments. There was a correlation between the soil fertility categories and key laboratory measurements, namely pH, OC, available N and soil physical characteristics. This finding is consistent with the responses on soil fertility indicators, namely soil colour (related to OC), water holding capacity (related to texture and OC). These results support findings of previous studies (Dawoe et al., 2012; Yageta et al., 2019) which reported that farmers largely relied on texture and colour as soil fertility indicators.

The differences in soil properties in fertile and infertile sites (Table 4.19) are likely to have resulted from past soil fertility management, rather than inherent soil properties. Soil cations recorded low values in poor compared to the fertile soils which was mainly due to higher organic matter content on fertile sites (Hoffmann et al., 2001). Exchangeable soil bases and pH are mainly influenced by soil organic matter (SOM) and the clay content. Given that the clay types and quantities were almost similar in both fertile and infertile sites, the differences in soil cations and soil reaction (pH) are likely to have resulted from differences in soil organic carbon (Gachene & Kimaru, 2003; Weil & Brady, 2016). Woomer et al. (1998) described the on-farm mechanisms that typically lead to soil variability in small-scale farming systems in central Kenya. Small-scale farmers typically manage livestock sheds and home gardens in “homesites” while “in-fields” include valued crops intended for markets. Fodder grasses are typically grown within outfields with minimal fertilizer inputs, and harvested for livestock in the “homesites”. The continuous nutrient mining of “outfields” leads to infertile sites within farms. Within the “in-fields”, farmers tend to grow preferred crops where inputs are applied, thus organic matter and nutrients tend to accumulate in the “homesites” and “in-fields”, at the expense of “outfields” leading to on-farm soil variability.

The multivariate findings from qualitative and laboratory soil measurements show that the components extracted from the original soil quality measures were closely linked to the soil quality indicators and functions proposed by Doran and Parkin (1996). In relation to the qualitative soil matrix, the first and second components were associated with the chemical and biological soil processes, including nutrient cycling, water relations, buffering, biodiversity and filtering processes. The factor analysis discriminated the soil physical component (component 3) as described by water holding capacity and soil workability loadings. Cornelis et al. (2019) recorded positive and significant correlation coefficients between a soil quality index and soil physical characteristics for bulk density, air capacity, air permeability, and hydraulic conductivity. The correlation with a farmer-descriptive index of soil quality ranged between 0.56 and 0.77 Our findings corroborate the patterns in Cornelis et al. (2019) who recorded a significant correlation between integrated soil quality scores and the water retention curve, especially under favourable soil conditions ($r > 0.50$).. Similarly, Adeyolanu and Ogunkunle (2016) demonstrated significant and positive correlations between qualitative and quantitative soil quality assessment measures in South-Western Nigeria. The findings of the current study show that there was a general relationship between measured soil quality parameters and farmer assigned score. The relationship was stronger in the high fertility fields, as shown by the mean soil quality score data and the regression between the additive and the farmer-descriptive SQI grouped by field categories. The relationship between qualitative and quantitative soil indicators can be explored within diverse agro-ecosystem contexts including soil types, land-use and agro-ecological zones.

4.2.4 Relationship between Farm management practices, socio-economic and soil quality

4.2.4.1 Farm management practices and soil properties

There was a positive correlation between agroforestry and CEC, Exchangeable bases (Ca, Mg), pH, OC, soil nutrients (P) and texture (sand and clay). Fallowing influenced Base saturation, Exchangeable cations (Ca, K, Mg, Na) and pH. Mixed farming correlated with exchangeable cations (K, Mg) and available N. Farms that applied manure showed high values for BS Extractable K, exchangeable cations (Mg, Ca, K) and pH. Mulching correlated positively with CEC, Mg, K, Ca, P and N, while retention of crop residue on the farm explained was associated with CEC, OC, N and moisture.

Farm trees are critical in reversing the negative effects posed by continuous tillage on soil physical properties including texture, structure and bulky density which influence vital soil functions such as water infiltration (Willy et al., 2019). Tree roots hold the soil together thus mitigating it against erosion and other threats to agricultural production (Blaser et al., 2017; Jose, 2009; Tscharntke et al., 2011). The leaves from the farm trees influence the build-up of organic matter which act as binding agents, further influencing soil pH and availability of soil nutrients and thus improving soil fertility. Other benefits of agroforestry include buffering against climate change, pathogen regulation and carbon sequestration (Blaser et al., 2017; Kwesiga et al., 2003).

The results suggest that farms that practiced fallowing had higher values for Base saturation, Exchangeable cations (Ca, K, Mg) pH and low Na content. Fallowing allows for soil rejuvenation in terms of soil structure and the overall soil fertility. A study by Don and Schumacher (2011) showed that there was an increase of 25% in SOC within 20 cm depth when cropland was converted to fallow. In another study by Chen et al. (2015), sites without any land use registered an increase in carbon stock by 0.19% within 15 cm depth. These studies clearly demonstrate that agricultural land use can have an adverse effect on soil fertility. Practices such as continuous tillage can interfere with the biological composition of the soil including microorganisms' activities (Gómez et al., 1999; Rolando et al., 2018).

Manure application was associated with high values for BS Extractable K, exchangeable cations (Mg, Ca, K) and pH. Organic resources have the potential to enhance soil productivity and improve crop yields in SSA. Manure contains critical plant nutrients including N, P, K. Additionally, solid manure contains substantial concentration of Ca and Mg and $CaCO_3$ (lime).

The organic matter supplied through manure application acts as pH buffer (Manitoba, 2013). Similarly, the solid proportion provides organic matter useful in enhancing the soil structure and fertility (FAO, 2001). However, the overriding challenge among smallholder farmers especially in SSA, is low quantity and poor quality of manure produced on the farm due to a small number of animal stock, and substandard manure management practices (Ndambi et al., 2019).

The results suggest a correlation between minimum tillage and various soil properties including CEC, BS, K (extractable and exchangeable), Mg and P. Mulching generally enhances soil quality by improving soil biological activities,, and promoting desirable chemical and physical soil properties (Cooper, 1973; Hanada, 1991; Ni et al., 2016). It improves plant growth by enhancing suitable soil moisture content and nutrients in the root zone (Ni et al., 2016). Mulching is critical in buffering soil temperature, and suppressing weed germination and growth. Mulch also protects the soil from soil erosion and compaction. The influence of minimum tillage on soil quality has been supported by several studies (e.g. Alam et al., 2014; Bronick & Lal, 2021; Lopez-Garrido et al., 2012; Munoz et al., 2007; Page et al., 1982).

Similarly, retention of crop residues minimizes soil water loss through evaporation (Iles & Dosmann, 1999; Ni et al., 2016; B. Singh et al., 1988). Recycling of crop residues through incorporation into the soil enhances the physical, chemical and biological properties (R. K. Singh et al., 2019). Crop residues enhance soil aggregates stability (Sonnleitner et al., 2003). improves soil water infiltration (Ekwue, 1992). and promotes the build-up of N, P, K and SOM (R. K. Singh et al., 2019).

4.2.4.2 Variability of soil fertility across Farm typologies

This study identified 3 farm types based on influential soil properties determined by FA. The conducted land quality classification yielded reasonable discrimination of soil fertility conditions across household farms.

There was significant variation in soil fertility status between the 3 farm types as indicated by differences in the averages of key soil attributes, including pH, SOC, CEC, extractable K, available P, Base saturation, sand proportions and exchangeable bases. The significant differences in SQI averages, suggest a consistent variation in soil fertility across the three farm types, delineating the farms as low fertility (cluster 1), moderate fertility (2) and high fertility (3). It is however important to note that values of soil fertility indicators for most samples were above average levels based on published SQI thresholds (Amacher et al., 2007). This could be due to the generally fertile soils in the region, which is in fact considered high agricultural potential area (Ariga & Jayne, 2011). The variability in soil properties could be attributed to differential management practices dictated by households' socio-economic characteristics.

Farm type 1 farms were characterized by low values for clay proportions, available P, pH, SOC and exchangeable bases (K and Mg). The values for P and SOC were very low, and the soils were moderately acidic (Amacher et al., 2007). This is expected because of the relatively high sand-clay ratio. Nevertheless, the average sand levels are generally within the acceptable range (<50%) (Amacher et al., 2007). Studies on African farming systems (e.g. Dembe´le´ et al., 2000; Rotich et al., 1999), have shown that the magnitude of SOC tended to vary between farm types. The low fertility of farms in this cluster could be attributed low use of organic and inorganic fertiliser and composted crop residues. Socio-economically, households in cluster 1 had smaller family sizes, smaller farm sizes with low income. These variables constitute the key household characteristics that have been used to explore farming system diversity (Kuivanen et al., 2016). The low consumption of fertilizer in this cluster could be attributed to low on-farm income limiting farmer's access to soil fertility resources (Tittonel et al., 2010). Alternatively, this cluster consists of households with young families with the household head most likely to be in formal employment considering a high proportion have attained above high school education. This would imply that their participation in farming is largely on part-time basis. Smaller land sizes are expected in this cluster, since land is inherited by the household head, thus fragmentation into smaller parcels (Kuivanen et al., 2016).

Cluster 2 farms have moderate average values for extractable K, clay, pH, CEC and exchangeable Ca. The fields have high SOC, BS and sand content. Moderate fertility status in these fields could be explained by the modest fertilizer application rates (Table 4.27). The proportionally, higher cases of fallowing contribute to the restoration of soil nutrients. The households within this cluster are largely headed by older, females with high farming experience and access to extension. Family sizes are moderate (larger than cluster 1) with above-average resource endowment in regard to farm size, income, and livestock units. These results are consistent with the findings of Kuivanen et al. (2016) in Ghana which reported a positive correlation between family size, livestock size and the age of the household head. In their typology of rural farm households, Bidogeza et al. (2009) in Rwanda, and Tittonel et al. (2010) in Kenya, found that age was a significant discriminant of cluster membership. However, in other findings none of the family's head attributes nor socioeconomic variables predicted cluster membership (cf. Dossa et al., 2011). In our study, age was less discriminant, perhaps due to the diverse characteristics of the farming households in the study area.

Farms in cluster 3 were the most fertile as shown by high values for clay content, pH and exchangeable K and moderate SOC. The difference in SOC between farm type 2 and 3 could be due the effect of fallowing in the former which allows for the build-up of organic matter from the accumulation of litter (Willy et al., 2019). High intensity fertilizer application, agroforestry and composting of crop residues observed among the farms in this category are important contributors to soil fertility. Similarly, the households in this cluster are characterized by high income, larger farms, high livestock volume, and larger families and workforce, which constitute key indicators of wealth (Köbrich et al., 2003; Tittonell et al., 2010). This clustering is consistent with Tittonell et l. (2010) study in East Africa in which farms within a wealthier farm type were characterized by larger livestock volume, large farms with cash crops and high income mostly generated from farming activities. The influence of income (especially off-farm) in technology adoption is widely acknowledged (Goswami et al., 2014). Resource-endowed households have ready access to large volumes of inorganic fertilizers and manure (Chikowo et al., 2014). In addition to contributing to household income, livestock provides manure which is used to enhance soil fertility. In this study, the intensity of household's consumption of animal manure is implicitly implied from the livestock volume (TLU). However, we note that the actual determination of the amount of manure used per unit area would have been more interesting. Farm labour which is often dictated by the household size (positively correlated) is a key driver of technology adoption and a major indicator of household diversity (Mugwe et al., 2009; Tittonell et al., 2010). Farming is the main occupation of the household heads, with majority of them having attained lower than high school level education. High degree of dedication to farming is thus expected and commitment to improve agricultural productivity (evident from higher fertilizer application rate) (Tittonel, 2010). Operational management and labour allocation have been shown to influence farm productivity and the efficiency of resource utilization (Tittonell et al., 2006). Households in this farm type have a high propensity of access to agricultural advice, including information on soil, crop and livestock husbandry which may also have contributed to sound soil fertility management (Gondwe et al., 2017).

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The aim of this study was to evaluate soil quality in Mount Kenya East region, determine farmers' soil fertility knowledge and to correlate soil fertility with household characteristics and management practices. The following specific objectives were undertaken: 1) characterization of soils of Mount Kenya East region; 2) identification of soil fertility management practices and determination of drivers of adoption of these practices; 3) determination of local soil fertility indicators and comparison of farmer and scientific soil fertility assessment; and 4) evaluation of the relationship between household's socio-economic and management characteristics and soil quality.

The first specific objective was to describe the soils of Mount Kenya East. Characterisation of soils on farms indicate that soils in Meru and Tharaka Nithi were generally moderately fertile. Specifically, these soils are characterized by low pH (5.4), low organic carbon, low exchangeable bases, and inadequate plant minerals. Deficiencies in exchangeable cations, partly contributes to soil acidity. Moderate levels of SOC in the region could be attributed to reasonable utilization of organic soil fertility resources as well as topological and climatic factors. In terms of soil nutrients, available P was low while extractable K was high. Available N ranged from low to moderate, and this could be explained by the nature of farm management practices, namely use of manure (which was applied in small amount). As part of interventions, there is a need for increased application of both organic and inorganic resources to ameliorate conditions unfavourable for crop production.

Soil classification identified 8 reference soil groups, namely Nitisols, Acrisols, Cambisols, Leptosols, Andosols, Gleysols, Plinthosols and Umbrisols. Nitisols, were the most predominant soil, occurring largely in the uplands (slopes of Mount Kenya), and considered as one of the most productive soils due to their deep and stable structure and desirable soil organic matter content. Acrisols, which are strongly weathered with low BS, were predominant in lowlands (southern parts of the study area). There were significant variations in soil properties across the RSGs, suggesting differences in fertility status.

The second objective was to identify soil fertility management practices, and to determine drivers of adoption of these practices. Fertilizer and manure application and agroforestry were the most common practices employed by farmers. Correlations between the various ISFM practices, suggests that households often adopt a bundle of technologies (which complement or substitute each other) as opposed to the entire ISFM package, based on their needs as well as resource constraints. The decision to invest in fertility practices was significantly correlated with several farmers' socio-economic, farm-related factors and institutional characteristics. On-farm labour and household size influenced manure and fertilizer adoption. Livestock quantity had a bearing on manure use. The relationship implies on the need to adapt the ISFM techniques to the local environment. Farmers have different assets which determine how they can apply techniques of their choice, and therefore exploring which practices make more sense depends on farmer's assets such as capital and labour.

The third objective was to determine farmers' perception of soil fertility and to compare farmers' and scientific soil fertility ssessment. Evaluation of farmers' soil fertility perception showed that farmers' knowledge provided a consistent and logical classification of soil quality. Fertile fields were associated with darker soil colour, numerous earthworms, indicator weeds, and plot locations in valley bottoms. Farmers' soil knowledge was substantiated using laboratory soil tests whereby soil pH, soil carbon, silt, sand and available -N were significantly different between soil fertility categories, implying that there was a qualitative difference in soils that had been characterized as different by farmers.

There was a correlation between farmer-descriptive SQI (F-SQI) and the two scientific SQIs, namely additive SQI (A-SQI) and the multivariate (Factor analysis) soil quality index (FA-SQI). There was a stronger relationship between F-SQI and the A-SQI in fertile than infertile plots. The soil quality indices derived from farmers' and scientific soil fertility assessments showed that there was a significant linkage between the two soil fertility assessment paradigms, thus calling for closer examination of farmers' soil knowledge systems and better collaboration between farmers' soil knowledge and technical soil knowledge systems.

The fourth objective was to determine the influence of farmers' socio-economic characteristics and management practices on soil fertility. There was a positive correlation between agroforestry and CEC, Exchangeable bases (Ca, Mg), pH, OC, soil nutrients (P) and texture (sand and clay). Fallowing influenced Base saturation, exchangeable cations (Ca, K, Mg, Na) and pH. Mixed farming correlated with exchangeable cations (K, Mg) and available N. Farms that applied manure showed high values for BS extractable K, exchangeable cations (Mg, Ca, K) and pH. Mulching correlated positively with CEC, Mg, K, Ca, P and N, while retention of crop residue on the farm was associated with CEC, OC, N and moisture.

To clearly understand the influence of farm management practices and socio-economic characteristics on soil quality, cluster analysis was performed to group households into farm typologies (farm types). The proposed typology enabled the identification of three farm types (clusters) representing infertile farms (FT1), moderately fertile farms (FT2) and fertile farms (FT3).

The resulting group membership and the statistical tests suggest that most variables representing diversity of household and farm characteristics had significant discriminating power, implying the distinctness of the identified farm categories.

The three identified farm types differed in several dimensions. The typologies differed both in their degree of soil heterogeneity as well as farm practices and socioeconomic characteristics.

FT1 are characterized by low values for important soil fertility indicators, including SOC, pH, CEC, available P and exchangeable bases (K and Mg). On the account of farm management practices, the low fertility could be explained by low application of fertilizer and organic resources. In turn, the observed management practices are influenced by smaller household size, lower income, and smaller farm size.

FT2 have higher levels of SOC, available P, exchangeable Mg and moderate measurements for CEC, extractable K and pH. The possible determinants of the observed fertility status include fallowing, use of composted residues (manure) and above-average fertilizer application rates. The correlated household characteristics include moderate income, family size and farm size. FT3 farms exhibit relatively desirable values for key soil fertility indicators, including SOC, pH, CEC, extractable K, available P and exchangeable bases (K and Mg). In relation to farm management practices, the high fertility could be attributed to high application rate of fertilizer and organic resources. Similarly, the observed management practices are influenced by favourable household socio-economic conditions including larger household size, higher income, and larger farm size.

Delineation of farms based on the various parameters including resource endowment underlines imbalanced farm resource flows suggesting a need to address the inequality in farm resource availability to reduce high soil quality variability and enhance the productivity and sustainability among smallholder farming systems. FT1 consisted of younger farmers that largely depended on off-farm employment, while FT2 was defined by moderately wealthier farms courtesy of significant investment in farming including good fertility management practices and cultivation of cash crops. FT3 was defined by wealthier farms courtesy of large farming land with cash crops and high livestock density (under intensive management).

The proportion of households falling in each farm type has implications when it comes to designing agricultural support programs or technologies, and thus this proposed typology may contribute to better targeting innovations. Households that demonstrate a more-agriculture-based livelihood strategies are more likely to respond positively when it comes to implementing and adopting agricultural intensification technologies, and thus should be targeted.

5.2 Recommendations

Based on the findings, this study proposes the following recommendations

- Smallholder farmers in Mount Kenya East, and by extension, in Kenya, should be encouraged to embrace the use of both organic and inorganic resources to improve soil fertility and agricultural productivity. Increasing the use of organic resources such as manure to 60 kg N ha^{-1} has the potential to increase maize yields from the current 0.5 to 1.5 t ha up to 4 to 6 t ha^{-1}
- It is imperative for the Kenya's County governments to strengthen extension services to enhance dissemination of information on the use of ISFM practices. The significant relationship between access to extension and adoption of some ISFM practices, point to the continued importance of agricultural extension. Capacity building of extension providers by equipping them with skills on soil fertility management is crucial. Establishment of demonstration sites and organizing of field days can increase adoption of the desired farm practices.
- Policymakers should formulate innovative financing opportunities to provide credit to farmers and promote profitable start-up projects especially among the youthful farmers, whom their participation in agriculture is often constrained by lack of capital. Creating an enabling environment can facilitate their investment capacities in soil fertility management practices. This intervention will also resolve the challenge of labour shortage as observed in this study.
- The correlation between farmers' soil knowledge and scientific soil systems suggests for more collaboration between scientists and farmers. Innovative soil fertility assessment and shared communication between scientists and farmers are needed to improve soil fertility management in low-input-low-output farming systems of the SSA. Integrated soil fertility assessment methodologies within similar agro-ecological zones and socio-economic settings may enhance communication between multiple stakeholders and improve soil fertility management among smallholder farming systems.
- There is a need to address the inequality in farm resource availability to reduce high soil quality variability (as demonstrated by farm typology) and enhance the productivity and sustainability in the farm system. Resource endowment was a significant discriminant between farm types and thus in reinforcing the cycle of imbalanced farm resource flows. Again, this emphasizes on the importance of capital in agriculture

Further research

- While the current study has achieved general conclusions regarding how farmer and scientific soil measurements were related, more innovative, comprehensive and systematic studies are needed to clarify the integration of soil knowledge between local and technical paradigms in diverse farming systems. Additionally, future research could also explore the local terminology in the study area for soil names based on the key indicators, namely texture and colour, to enhance a two-way communication between the extension providers and farmers.
- While this study made great strides in discriminating farm types based on fertility status, more research should be targeted towards smallholder farming systems to improve understanding of soil fertility dynamics in these farm types. This study suggests for the inclusion of additional relevant parameters in the initial model (PCA) and with a larger sample size (which can yield a potentially realistic number of clusters/farm types that reflect the general reality observed during field survey). Considering that in the current study, variable selection for cluster analysis was achieved strictly by methodological approach based on PCA (CATPA and FA), incorporation of expert opinion is suggested for future studies.
- In regard to comparing farmers' and scientific soil fertility assessment, further research could improve our study by modelling with more soil parameters including biological parameters and identifying the specific weed species associated with high and low soil fertility.
- Both extensive and intensive within-farm soil sampling is recommended for future research on soil fertility. In this study, samples were obtained from only one sampling point per farm. Within-farm soil fertility gradient (arising from preferential application of soil fertility resources based on perceived field's soil quality) is a common phenomenon among smallholder farming systems in SSA and thus should be taken into consideration as it is important in facilitating resource allocation in these farms. Control environment is recommended for quality data

6 KEY SCIENTIFIC FINDINGS AND IMPORTANT OUTPUT

1. Properties of soils in the study area were determined, and this facilitated the estimation of the general soil fertility status in the region based on the measured laboratory data and published SQI indicators. Similarly, the identified RSGs were correlated with soil properties to determine variation in their fertility status. A connection was drawn between reference soil groups and soil fertility in a local context (larger scale), making this study, the first one to investigate fertility variation across RSGs in the area of study.
2. Through clustering, farmers' combination patterns of soil fertility management practices were determined. This study used multivariate analyses, which are critical in capturing the true picture among smallholder farmers. This is useful in identifying areas of policy intervention.
3. In this research a Farmer-descriptive SQI was systematically developed and used to classify soils (as either fertile or infertile). Most of (if not all) the previous studies that have investigated the relationship between farmers' and scientific soil assessment, simply asked farmers to identify fertile and infertile fields. In this study, farmers rated the fertility of their soils based on the various indicators. The scores were summed and then averaged to give the final soil fertility rating (from the farmer's perspective).
4. By comparing farmers' perception of soil fertility against scientific assessment, this study validated local soil fertility classification system. Farmer-descriptive SQI and two scientific fertility assessment methods (FA-SQI and additive SQI) were compared. Local knowledge was largely consistent with substantial scientific attributes. A substantial attempt to quantify qualitative soil parameters was made.This study lays a good base for an integrated location-specific soil management guideline.
5. Farm households were classified into 3 farm types, following a systematic methodological typology approach, based on soil variability and the identified clusters characterized based on farm management practices and socio-economic factors. The farm typology methodology (grouping of farms/households into common or similar groups) used in relating farm characteristics was key in understanding and dealing with variability and diversity and appreciating of both the farm management and household characteristics that explain the variation in soil fertility. Multivariate analysis (CATPCA, FA and CA) were used. This approach is useful in identifying resources allocation patterns. It provides a good framework for futher studies focusing on

exploring differences in challenges, opportunities, efficiencies in resource allocation and dissemination of innovation as well as identifying potential areas of collaboration.

SUMMARY

Soil is the primary ingredient of agricultural production, yet cases of declining soil fertility have been spiralling and thus a major concern among policy makers globally. The goal of this study was to assess soil resources, farmers' knowledge and management practices and their possible influence on soil quality, in Kenya, using Mount Kenya East region as a case study. To achieve this aim, four objectives were pursued. The first objective was to characterize soils of the study sites. Secondly, soil fertility management strategies used by farmers were identified and determinants of adoption determined. The third objective examined farmer's knowledge of soil fertility and compared the local fertility assessment with scientific estimations. The final objective evaluated the influence of farm household's socio-economic and farm management characteristics on soil quality. To chieve these objectives, both natural and social science approaches were used.

The study was conducted in Mount Kenya East, encompassing 2 counties, namely Meru and Tharaka Nithi, located on the eastern slopes of Mount Kenya, approximately 200 km from Kenya's capital, Nairobi. Agriculture is the primary economic activity in the region, with farming dominated mostly by smallholder farmers. Agriculture is mainly rain-fed and characterized with diverse agricultural production. The region is a traditionally high agricultural productivity zone attributed to favourable climatic conditions and fertile soils. However, emerging decline in soil fertility poses a major threat to the community's livelihood, thus the importance for this study. Comprehensive knowledge of soils and soil properties is essential in realizing sustainable land use.

The data used in this study was obtained through farm household survey (questionnaire and interview) and soil sampling conducted between January-March 2019. Conditioned Latin Hypercube sampling (cLHS) was used to determine sampling sites. About 150 farms were initially identified for sampling. However, soil samples were collected from 69 farms. At each household farm, soils were sampled from one field at three depths: 0-20 cm, 20-50 cm and 50-100 cm. One hundred and six farm households (including those from which soil was sampled) were surveyed for the questionnaire. Semi-structured interviews for farmers and extension officers were used to supplement data obtained through the questionnaire.

Laboratory soil analysis was performed using 40 representative samples (out of approximately 207 samples) determined based on multivariate calibration techniques (chemometrics). Partial Least Squares Regression (PLSR) with leave-one-out cross validation was used to calibrate the

MIR spectral data with the reference laboratory soil data. Soil classification of the visited sites was conducted based on the World Reference Base of soil resources (WRB) 2014 and soil classification guideline (IUSS Working Group WRB, 2015). Eight RSGs were identified. Principal component analysis (PCA) and multiple correspondence analysis (MCA) were performed for soil properties (numeric) and RSGs (categorical), respectively, to compare variability of soil properties.

To achieve the second objective, questionnaire data from the entire 106 sample was submitted to appropriate analyses packages. Fisher's exact test (FT) and Welch's t-test (WT) were used to examine the significance of the associations between the explanatory variables and adoption of soil fertility management practices.

In relation to objective three, farmers' description of fertile and infertile soils was generated using descriptive statistics. Factor Analysis was used to analyse soil fertility indicator scores generated by farmers to determine the major soil quality dimensions within farmers' fields in the study sites. To compare farmers and scientific soil fertility assessment, farmer-descriptive SQI (F-SQI) was regressed against two scientific SQIs, namely additive SQI (A-SQI) and Factor Analysis (FA-SQI). The farmer descriptive SQI was generated by averaging the sums of local indicator scores for each field, resulting into an aggregated farmer criterion for soil quality assessment. A-SQI was developed based on measured soil properties threshold levels following procedures outlined by Amacher et al. (2007) and Vlek et al. (2010). FA-SQI was developed based on multivariate analysis.

To examine the influence of household and farm management characteristics, farm typology was developed using Categorical Principal Analysis (CATPCA) and Factor Analysis (FA), followed by cluster analysis (CA) using Two-Step and hierarchical clustering methods. After clustering, ANOVA and Fisher's Exact Test (FET) analyses were used to compare socio-economic attributes, farm management parameters and soil characteristics between clusters.

Results of soil characterization suggest that the soils in the Mount Kenya east region are generally acidic (average pH 5.4), and highly leached (low exchangeable cations) with low organic carbon. Soil classification identified 8 reference soil groups. Nitisols were the most predominant soil, occurring largely in Meru County, and considered as one of the most productive soils due to their deep and stable structure. Acrisols, which are strongly weathered with low BS, were predominant in Tharaka Nithi County. Other RSGs include Cambisols, Leptosols, Andosols, Gleysols, Plinthosols and Umbrisols.

Fertilizer and manure application and agroforestry were the most common practices employed by farmers. Correlations between the various ISFM practices, suggests that households often adopt a bundle of practices based on their needs as well as resource capacities. The decision to invest in fertility practices was significantly correlated with several farmers' socio-economic, farm-related factors and institutional characteristics. The relationship points to the need to adapt the fertility management techniques to the local environment.

The comparison between farmer and scientific soil fertility assessment suggests a linkage between F-SQI and the two scientific systems, implying that farmers' knowledge provided a consistent and logical classification of soil quality. The linkage between the two soil fertility assessment paradigms calls for closer examination of farmer soil knowledge systems and better collaboration between farmer soil knowledge and technical soil knowledge systems.

Farm typology based on soil characteristics clustered farm households in Mount Kenya east into 3 farm types. The most important variables (soil characteristics) that discriminated between farm types include pH, soil organic carbon (SOC), cation exchange capacity (CEC), available P, extractable K and exchangeable bases, typifying farms as infertile (Farm type 1), moderately fertile (FT 2) and fertile farms (FT 3). Discriminatory farm characteristics included fertilizer application intensity and fallowing. Socio-economic variables that distinguished farm types include farm size, income and household size (labour). Delineation of farms based on the various parameters including resource endowment underlines imbalanced farm resource flows suggesting a need to address the inequality in farm resource availability to reduce high soil quality variability and enhance the productivity and sustainability among smallholder farming systems.

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APPENDICES

Appendix A FARM-LEVEL QUESTIONNAIRE

INTRODUCTION

This questionnaire survey seeks to collect data for purposes of a PhD research. The information collected will strictly be used for accomplishing the stated academic objective and shall be treated with **utmost confidentiality** and will **not** be disclosed to a third party unless where consent is sought and granted. Demographic data will be used only for statistical analysis.

I would be more than glad if you would help in responding to the questions in this questionnaire. Feel free to skip any question that you are uncomfortable providing a response to. Answering this questionnaire would take you about 30 minutes.

Farm ID_______ **Coordinates_______________**

COUNTY______________ SUB-COUNTY_________________WARD_______________

A. SOCIOECONOMIC DATA

1. How many people are there in your household? ___________
2. How many family members are actively involved in farming? …………………………
3. What is your primary occupation? ____________________________________
4. For how long have you been in farming?_________________________________
5. What is the range of the total size of your farm in acres?........................(provide actual size)

   A. Less than 1 ☐ B. 1-3☐ C. 4-6 ☐ D. 6-10 ☐ E. more than 10 ☐

6. Approximately what proportion of your farm is under trees? ……………………..%
7. What type of farming are you engaged in?

A. Crop farming ☐ B. livestock farming ☐ C. Both Crop and Livestock farming

8. Approximately what is the proportional contribution of the practised farming enterprise to the household's income?..........................

   A. Strictly subsistence B. Less than 10% ☐ C. 11-25% ☐ D. 26-50% ☐

   E. 51-75% ☐ F. 76-100% ☐

9. Of the following crops grown on your farm, which one do you consider as the most important crops? Please give the importance of the crop (zero [0] to 10); zero (0)

indicating the crop not grown, 1 indicating not so important, and 10 being the most important cop.

10. What are the reasons for growing the specific crops?

Use Table 1 for responses to questions 9 and 10

Table 1: Crops grown and reasons for cultivation

S/N	Crops grown	9. Rate of importance (1-10)	10. Reason
1	Maize		
2.	Rice		
3.	Tea		
4	Coffee		
11.	Vegetables		
12.	Legumes		
13.	Potatoes		
14.	Fruit crops		
15.	Sugarcane		
16.	Bananas		
17.	Pasture		
18.	Other (specify)….		
19.	Other (specify)….		
20.	Other (specify)….		
			1) Soil suitability 2) income generation 3) size of the land 4) suitable climatic conditions 5) traditional crop (culture) 6.other, please specify

11. What mode of cropping system do you practice on your farm?

A. Pure stand ☐ B. mixed cropping ☐ C. Agroforestry ☐ D. Other (specify)☐__________

12. Which type of livestock do you keep on your farm? (Please fill in the table)

Table 2: Livestock data

S/N	Livestock	Approximate Number
1	Exotic dairy cattle	
2	Indigenous dairy cattle	
3.	Beef cattle	
4	Goats	
5	Sheep	
6	Poultry	
7.	Fish farming	
8	Other (Specify)………………………	
9	Other (Specify)………………………	
10.	Other (Specify)………………………	

13. What is your approximate annual household income? (answer using the table below)

Table 3: Income data

S/N	Source	Approximate average monthly income	Approximate annual income
1.	Crop farming		
2.	Livestock (sale of milk or animal)		
3.	Employment (salary)		
4.	Wages from informal jobs (specify)		
5.	Business (off farm business)		
6.	Pension		

S/N	Source	Approximate average monthly income	Approximate annual income
7.	Remittances (support from children)		
	TOTAL		

B. SOIL FERTILITY MANAGEMENT STRATEGIES

Use Table 4 for responses to questions 14 and 15

14. Which of the following soil fertility management strategies do you practice on your farm (you can select more than one, as applicable)
15. Can you see any constraints to the non-use or limited use of the strategy?

Table 4. Fertility Management practices

Soil fertility management strategy	14. Yes/No	15. Any constraint(s) to non-use or limited use of the strategy
Slash and no-burn		
Burning of crop residues		
Application of crop residues		
Retention of trees on croplands		
Application of manure		
Application of inorganic fertilizer		
Minimum tillage (chemical weed control)		
Fallowing		
Other (specify)……………………..		
		1= Termite infestation, 2=bushfires, 3=tree felling (timber, construction materials, firewood,

Soil fertility management strategy	14. Yes/No	15. Any constraint(s) to non-use or limited use of the strategy
		charcoal), 4=too much shade, 5=lack of transportation means, 6= lack of knowledge (e.g. in preparation of manure, spraying techniques/procedures), 7= laborious (e.g. bulky manure), 8= scarcity, 9=smell and odour, 10=high cost (of fertilizer, spraying machines, 11=land fragmentation, 12=high population 13.other (specify)……………..

16. How do you manage crop residues after harvesting your crop? (you can choose more than one, as applicable)

A. Burning ☐ B. Composted ☐ C. incorporated in situ ☐ D. Used as fodder ☐

E. Used for fuel ☐ F. Other (specify): ☐ ________________________

17. How often do you leave your farm fallow after harvesting your crop?

A. I plough it immediately ☐ B. less than one month ☐ C. 1-4 months ☐ D. 5-6 mont ☐
E. Other (specify) ☐ ________________________

Use Table 5 for responses to questions 18 and 19

18. Which tree crops do you grow on your farm?

19. Do you have any special reason for your choice of tree types?

Table 5: Tree crops data

s/n	18.Name of tree crop	19. Reason for growing the tree
1.		
2.		
3.		
4.		
5.		Reasons: 1. Control erosion, 2. Aesthetic purposes, 3. Air purification,

s/n	18.Name of tree crop	19. Reason for growing the tree
		4. Boost soil fertility 5. Food (family consumption), 6. For sale 7. For shading 8. Pest management 9. Other (specify)…..

Inorganic fertilizers use on the farm

Use Table 6 for responses to questions 20 and 23

Table 6. Inorganic fertilizer use

	Activity	Response	Choices
20	Do you use fertilizer during planting of crops?		0=No, 1=Yes
21	How often do you use fertilizer when planting your crops?		A. Every planting season B. Only during main planting season C. sometimes (irregular)
22	Do you top-dress your crops with inorganic fertilizers?		0=No, 1=Yes
23	How often do you top-dress your crops with inorganic fertilizer?		A. Every growing season B. Only during main growing season C. sometimes (irregular) D. Rarely top dress E. Never

Use Table 7 for responses to questions 24 and 25

24. Which crops do you plant and/or top-dress using fertilizer?
25. What is the reason for your decision?

Table 7. Crops grown using inorganic fertilizer

S/N	Crops	24. (1=planted using fertilizer 2= top-dressed with inorganic fertilizer 3=both)	25. Reason
1.			
2.			
3.			
4.			
5			
	Codes: 1. Maize, 2. Beans, 3. Tea, 4. Coffee, 5. Vegetables 6. Potatoes, 7. Fruit crops, 8. rice		1=high value crop, 2= grown on infertile soils, 3) good returns, 4) only does well with fertilizer, 5) Crop demanded in large quantity (staple) 6) other (specify) ……………….99) DK

Use Table 8 for questions 26 to 31

Types and rate of fertilizer application

Table 8. Data on fertile use

26. Which Fertilizer type do you normally use?	27. Manufacturers	28. Source	29. Cost per kg	Application rate/acre	
				30. Planting	31. Top-dressing
DAP 18-46-0					
CAN 26%					
NPK 23.23.0					

26. Which Fertilizer type do you normally use?	27. Manufacturers	28. Source	29. Cost per kg	Application rate/acre	
				30. Planting	31. Top-dressing
NPK 22-6-12 +TE					
NPK 17-17-17					
NPK 25-5-5					
NPK 20.20.0					
TSP 46% P205					
UREA 46% N					
Sulphate of Ammonia 21%					
MOP 60% K20					
Other (specify)…………..					
	1= MEA, 2=Mavuno, 3= Chapa Meli, 4=Baraka, 5=Yara, 6=ETG, 7=OCP, 8=Yara 9=Springs 10=Turibo 11=Thabiti 12=TTFA 13=Minjingu 14=ICL	1= purchased from local agro-dealers , 2= government subsidized fertilizer, 3=loan from cooperative/contract farming, 4=donation from NGO,			

26. Which Fertilizer type do you normally use?	27. Manufacturers	28. Source	29. Cost per kg	Application rate/acre	
				30. Planting	31. Top-dressing
		5=Other (specify) …..			

Manure

32. Do you use manure on your farm?........................... 1. Yes 0. No

If yes, proceed to subsequent questions, otherwise jump to question 38.

33. Please indicate the type of manure used on your farm (Table 9).

34. What is the source of manure? (You can indicate more than one, as applicable)

Use Table 9 for questions 33 and 34

Table 9. Types and sources of manure

S/N	Form of manure	33. 0=No, 1=Yes	34. Source
1.	Farm yard manure		
2.	Poultry manure		
3.	Biogas slurry		
4.	Green manure		
5.	Compost manure		
6.	Fish pond manure		
7.	Goat manure		
8.	Cattle manure		
9	Other(specify)…………………		
	Sources: 1. Own farm 2. Free From neighbour 3. Purchase from neighbour 4. Purchase from next village 5. Purchase from market centre 6. Others (specify)……..		

Use Table 10 for questions 35 to 37

35. On which part of the field do you apply manure?

36. What are the crops cultivated on that field?

37. What is the reason for your decision to apply manure on specific fields?

Table 10. Manure use on different fields

S/N	35. Location of the field	36. Crops cultivated	37. Reason
1.			
2.			
3.			
4.			
5			
6			
7			
8			
9			
10			
	1. near homestead 2. middle field, 3. remote field 4. Even application of manure on the whole farm	*Codes: 1. Maize, 2. Beans, 3. Tea, 4. Coffee, 5. Vegetables 6. Potatoes, 7. Fruit crops, 8. rice*	*Reasons: 1. Near the homestead (little labour force required) , 2. High value crops, 3. Crops with high nutrient needs, 4. Low fertility plots Other (specify)….*

LOCAL KNOWLEDGE/PERCEPTION ON SOIL FERTILITY

Use Table 11 for questions 38 to 41

Based on the parameters listed in Table 11:

38. How do you characterize fertile soils?
39. How do you characterize infertile soils?
40. Rate the importance of the parameters in determining soil fertility.
41. Rate the overall quality of your soil.

Use Table 11 for questions 38 to 41

Table 11. Local soil knowledge

Parameter	**Criteria**		**Codes**	40. Rate the importance of the parameter in determining soil fertility on a scale of 1-5 (1= not important, 5= very important)	41. How good is your soil overall quality based on these parameters (0= very poor 1= poor 2= average 3= good 4=very good 5=excellent
	38. Fertile soil	**39. Infertile soil**			
Colour			1= dark, 2= white/pale/light, 3=Brown; 4=Red		
Soil workability			1=presence of few stones and pebbles , 2= difficult to work		
Water holding capacity			1=high WC, 2= low WC		

Parameter	Criteria		Codes	40. Rate the importance of the parameter in determining soil fertility on a scale of 1-5 (1= not important, 5= very important)	41. How good is your soil overall quality based on these parameters (0= very poor 1= poor 2= average 3= good 4=very good 5=excellent
	38. Fertile soil	**39. Infertile soil**			
Crop yields			1= consistently high yields, 2= low yields		
Crops growth rate			1=fast/high growth rate, 2=stunted/slow plant growth		
Colour of leaves			1= large green leaves, 2= small/stunted yellowish leaves		
Presence of earthworms (worm casts)			1=numerous wet worm casts, 2= fewer worm casts		
Presence of indicator weeds			Weeds that indicate fertile soils, and weeds		

Parameter	Criteria		Codes	40. Rate the importance of the parameter in determining soil fertility on a scale of 1-5 (1= not important, 5= very important)	41. How good is your soil overall quality based on these parameters (0= very poor 1= poor 2= average 3= good 4=very good 5=excellent
	38. Fertile soil	**39. Infertile soil**			
			that indicate infertile soils		
Topography (slope)			1= valley bottom slope, 2= lower middle slope 3=upper slopes		
Other(specify)…………..					

SOIL FERTILITY DECLINE

Use Table 12 for questions 42 and 43

42. Which of the following causes of decline of soil fertility affect your farm?
43. How would you rate the importance of these causes of decline of soil fertility?

Table 12. Soil fertility decline

S/N	Causes of soil fertility decline	42. Affect your farm? (0=No, 1=Yes)	43. Rating importance of causes of decline of soil fertility (Scale :1 to 5, 1: not important; and 5: very important)
1.	Continuous cropping		
2.	Low fertilizer application		
3	Low organic manure application		
4.	Deforestation		
5.	Low rainfall		
6.	Excessive rainfall		
7.	Erosion		
8	Any other :…………………………………………………………		
9.	Any other :…………………………………………………………		
10.	Any other :…………………………………………………………		

SOIL DEGRADATION PROCESSES

Use Table 13 for questions 44 to 47

44. Which of the following soil degradation processes affect your area?
45. Using a scale of 1-5, please rate the severity of the soil degradation processes present in your area,
46. In your opinion, what are the causes of soil degradation processes?
47. What are the strategies put in place to prevent soil degradation in this area?

Table 13. Soil degradation processes

S/N	Soil degradation process	44. Soil degradation processes present in your area? (0=No, 1=Yes)	45. Rating of Severity of soil degradation process (*1=no effect, 5=very severe*)	46. causes of soil degradation processes	47. soil degradation prevention strategies
1.	Soil erosion				
2.	Sealing				
3.	Soil compaction				
4	Loss of organic matter				
5	Desertification				
6	Soil contamination				
7	Biodiversity decline				
8	Salinization				
9	Acidification				
10.	Sodification				
11.	Any other (specify)………… …………………… ………..				
		Severity key: 0. No effect 2. Not severe 3. Slightly severe 4. Moderately severe 5. Strongly severe, 99= I don't know			

SOURCE OF INFORMATION ON SOIL FERTILITY

48. Have you ever received any information on soil fertility?
    YES ☐ NO ☐

49. If YES above, when was the most recent time you received the information?
    A. Less than 3 months ago ☐ B) 3-6 months ☐ C) 7-11 mo s
    D) 1-2 yea go E) 3-4 ye ago F) more than ears ago G) D t remember

Use Table 15 for questions 50 to 53

50. Which of the following extension information (services) have you received in the recent past?
51. What was the source (s) of the information received?
52. Please give the specific name (s) of the extension provider(s)
53. What was the cost of the service?

Table 15. Extension services

S/N	Nature of information(service)	50.Information (services) received (0=No, 1=Yes)	51. Source	52. Name of the institution	53. Cost of the service
1.	Soil analysis/testing				
2.	Soil fertility management practices				
3.	Credit facilities				
4.	Crop husbandry				
5.	Livestock husbandry				
6.	Agribusiness				
	Source: 1. Government extension agents, 2. Cooperative society, 3. NGO, 4. Research organization, 5. Farmer group, 6. Other (specify)				

54. In your opinion what are the constraints to soil fertility management in your area?
i) ____
ii) ____
iii) ____
iv) ____
v) ____

55. What do you think should be done to address soil fertility issues you have indicated?
i) ____
ii) ____
iii) ____
iv) ____
v) ____

56. DEMOGRAPHIC DATA

Name (optional): ________________________________

Contact______________________

Gender: Male ☐ Female ☐

Age: Below 20☐ 20-25 ☐ 26-30☐31-35 ☐36-40 ☐ 41-45 ☐ 46-50☐

51-55☐56-60 ☐ 61-65☐ 66-70☐ Above 70 ☐

Education level: Never attended schoo☐ Did not com☐e primary

C☐pleted primary Did not comp☐High school ☐th

school graduate Middle☐el college graduat☐ Bachelor's ☐ee

Post graduate

END

THANK YOU FOR YOUR TIME AND COOPERATION

Appendix B Farmer Interview

This interview seeks to collect data for purposes of a PhD research. The information collected will strictly be used exclusively for accomplishing the stated academic objective and shall be treated with **utmost confidentiality** and will **not** be disclosed to a third party unless where consent is sought and granted.

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A. Farming activities

1. What kind of agriculture do you practice on your farm? (livestock farming, crop farming)
2. How would you describe your farming systems under the following subheadings:
   a) Crop farming (single crop, mixed cropping)
   b) Livestock farming (zero grazing, semi-zero-grazing, free range)
3. Do you produce for commercial or subsistence purposes?
4. How is your land subdivided under various enterprises? (please illustrate using a sketch map)
5. What do you think about soil fertility on your farm? Are there any differences? (demonstrate using a schematic drawing/map).
6. How do you tell about the differences in soil fertility (indicated above)? (is it through experience, observations such as colour and other parameters)
7. How do you determine which crop/farming activity to place under a given plot?

B. Fertility Management strategies

8. What would you say about the trend in your soil productivity for the last ten years? (is it deteriorating, unchanged, increasing?)
9. If there are any changes what do you think might have contributed? (reasons)
10. What are you doing differently today or from the recent past?
11. How do you enhance the fertility of your soil?
12. Do you use mineral fertilizer? Why?
13. Do you apply organic fertilizer on your farm? Why?
14. What do you plan to do differently in future in managing your soil?

C. Cooperation of farmers and access to information

15. Do farmers cooperate in this region? (are they organized in groups? Based on what criteria?)
16. How do farmers access information (from extension, farmer-to-farmer, in groups)

D. Soil testing

17. **Are there soil testing services in the area? (**
18. **What is the criteria used in selecting farms for testing)**
19. How frequent is soil testing done? (**Has your soil ever been tested?)**
20. Who guides the farmers on when to have the soils tested,
21. Who provides the soil testing services?
22. Who pays for the services? (what is the approximate cost?)
23. Which soil parameters are tested?
24. How are the recommendations for soil management done?

E. Subsidy, incentives

25. Are there input subsidy programmes in your area? (describe its organization (who is the provider?), effectiveness, and any challenges)
26. Are there any other incentives that have an impact on soil fertility?
27. What do you think would motivate farmers to increase soil fertility?

END

THANK YOU FOR YOUR TIME AND COOPERATION!

Appendix C Interview for Extension providers

This interview seeks to collect data for purposes of a PhD research. The information collected will strictly be used for accomplishing the stated academic objective and shall be treated with **utmost confidentiality** and will not be disclosed to a third party unless where consent is sought and granted.

1. How would you describe farming activities in your jurisdiction?
   a) How many farmers are in this area?
   b) What are the major crops grown and livestock reared in this area?
   c) How has been the production trend in the past 5 years?
   d) What could be attributed to the observed trend?
   e) What are the major challenges experienced by farmers in this area?

2. Extension services
   a) How is it to work as an extension service provider in this area?
   b) How often do you visit farmers?
   c) Are there farmers groups in your area? Describe their activities and the working relationships with your office
   d) Are there farmers who come seeking for agricultural information?
   e) What type of information is highly sought by the farmers in the area?
3. Soil fertility and management
   a) Is soil degradation an issue in this area?
   b) What is your opinion in relation to soil fertility trends in the area?
   c) How would you describe soil fertility management in your area?
      a.
      b.
4. **Soil information & Soil fertility**

4.1 Is there any current documentation of soil resources in the area?

4.2 Do farmers get any information on soil?

4.3 What type of information?

4.4 How is the information communicated?

4.5 Are there any soil campaign activities in the area? (either sponsored by the government or non-governmental agencies)

4.6 How would you describe the link between extension and research?

5. Incentives

5.1 Do farmers in this area have access to subsidized inputs? Which ones?

5.2 Are there any incentives that have an effect (positive or negative)on soil fertility

5.3 What in your opinion, should be done to maximize farming profitability?

5.4 What in your opinion would motivate farmers to increase soil fertility?

Which farmer do you suggest for interview?

END

THANK YOU FOR YOUR TIME AND COOPERATION!

Appendix D Selected explanatory variables used in Fisher's Exact test

Table A 1. Fisher's Exact test of Relationship among selected explanatory variables

	Extension contact		Soil info		Soil Fert. Mngt		Credit info		Crp info		Livst info		Agribu info		Soil testing	
Variables	Coef	P>|z|	Coef	P>|z|	Coef	P>|z|	Coef	P>|z|	Coef	P>|z|	Coef	P>|z|	Coef	P>|z|	Coef	P>|z|
Gender	-0.028	0.463	0.005	0.606	0.167	0.070	-0.024	0.530	0.167	0.068	-0.109	0.190	-0.015	0.632	0.440	0.298
Age	-0.186	**0.043**	0.149	0.111	-0.147	0.106	-0.134	0.148	-0.135	0.126	-0.033	0.460	-0.244	**0.023**	0.164	0.126
Education	0.119	0.471	0.151	0.300	0.083	0.691	0.144	0.332	0.105	0.559	0.192	0.141	0.134	0.388	0.132	0.399
Location (County)	0.120	0.156	0.237	**0.024**	0.034	0.466	-0.034	0.537	-0.140	0.118	-0.008	0.589	-0.113	0.318	0.125	0.154
Farming as primary occupation	-0.075	0.335	-0.007	0.642	0.642	0.048	0.526	0.395	0.160	0.100	-0.188	0.074	0.060	0.697	0.078	0.376
Years in farming	-0.174	0.055	0.161	0.089	0.009	0.567	-0.123	0.176	-0.105	0.201	-0.109	0.190	-0.194	0.064	0.033	0.459

Table A 2. Correlation between Household Farm size and access to Government subsidized fertilizer using ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	5.186	58	0.089	2.884	0.000
Within Groups	1.333	43	0.031		
Total	6.52	101			

Table A 3. Correlation between Farmer's income and access to Government subsidized fertilizer using ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.693	18	.038	.573	0.910
Within Groups	5.845	87	.067		

Total	6.538	105			

Appendix E Significance tests of the relationship between Soil fertility management Practices and soil properties.

Table A 4. Descriptive statistics of manure application and soil properties

Group Statistics				
MANURE_APPLICN		Mean	Std. Deviation	Std. Error Mean
Ca (Cmol/kg)	No	0.069675	0.003182	0.00225
	Yes	2.05653	1.783914	0.213219
K (Cmol/kg)	No	0.106962	0.01251	0.008846
	Yes	0.397982	0.417446	0.049894
Mg (Cmol/kg)	No	0.02525	0	0
	Yes	0.723725	0.650452	0.077744
Na (Cmol/kg)	No	0	0	0
	Yes	0.05673	0.082876	0.009906
pH(H2O)	No	4	0	0
	Yes	5.521	0.8129	0.0933
pH(HCL)	No	3.8	0	0
	Yes	4.582	0.6252	0.0717
OC	No	1.786	0.028284	0.02
	Yes	1.19717	1.052745	0.124938
CEC	No	20.0435	6.305271	4.4585
	Yes	18.7521	8.678248	1.015712
BS %	No	1.0465	0.251023	0.1775
	Yes	18.18481	11.99435	1.454528
Clay %	Yes	36.18	12.965	2.103
	No	46		
moisture %	Yes	5.29	2.347	0.381
	No	7		
silt 2%	Yes	39.03	8.912	1.446
	No	37		
sand2 %	Yes	24.97	15.821	2.566
	No	18		
AL-P2O5	Yes	12.05	16.076	2.608
	No	18		
AL-K2O	Yes	322.89	268.037	43.481
	No	168		

Fallowing and soil properties

Table A 5. Descriptive statistics of Fallowing and soil properties

Group Statistics				
Fallowing		Mean	Std. Deviation	Std. Error Mean
Ca (Cmol/kg)	No	1.467905	1.1674250	.1801376
	Yes	2.748148	2.2182396	.4049933
K (Cmol/kg)	No	.279299	.2343732	.0361646
	Yes	.544736	.5478393	.1000213
Mg (Cmol/kg)	No	.546699	.4990901	.0770113
	Yes	.924996	.7751428	.1415211
Na (Cmol/kg)	No	.028137	.0584068	.0090124
	Yes	.092978	.0959043	.0175097
pH(H2O)	No	5.307	.8953	.1320
	Yes	5.734	.6851	.1211
pH(HCL)	No	4.446	.7086	.1045
	Yes	4.728	.4545	.0804
OC	No	1.23744	1.253884	.195824
	Yes	1.18238	.702777	.124235
CEC	No	19.22502	9.313661	1.404087
	Yes	18.16416	7.560853	1.357969
BS %	No	13.48346	10.973694	1.713803
	Yes	23.64959	11.397492	2.116461
Clay %	Yes	35.44	14.380	3.595
	No	37.13	12.031	2.509
moisture %	Yes	5.94	2.863	.716
	No	4.91	1.832	.382
silt 2%	Yes	37.81	9.425	2.356
	No	39.78	8.458	1.764
sand2 %	Yes	26.88	17.247	4.312
	No	23.35	14.662	3.057
AL-P2O5	Yes	7.69	11.677	2.919
	No	15.35	17.834	3.719
AL-K2O	Yes	382.13	268.169	67.042
	No	274.96	260.638	54.347
N (NH4-N+NO3-N)	No	24.03	23.086	3.795
	Yes	25.39	22.171	5.226

Agroforestry and soil properties

Table A 6. Descriptive statistics of Agroforestry and soil properties

Group Statistics				
Agroforestry		Mean	Std. Deviation	Std. Error Mean
Ca (Cmol/kg)	No	1.864050		
	Yes	2.245359	1.7329329	.3537334
K (Cmol/kg)	No	.086077		
	Yes	.511154	.4919278	.1004143
Mg (Cmol/kg)	No	.638750		
	Yes	.744495	.7598021	.1550939
Na (Cmol/kg)	No	.310435		
	Yes	.044375	.0749028	.0152895
pH(H2O)	No	5.250	.3536	.2500
	Yes	5.504	.8645	.1664
pH(HCL)	No	4.000	0.0000	0.0000
	Yes	4.537	.5408	.1041
OC	No			
	Yes	1.34750	1.371106	.268896
CEC	No	10.70900		
	Yes	21.03531	11.045709	2.166242
BS %	No			
	Yes	19.09371	13.908978	2.839158
Clay %	Yes	35.29	13.080	2.211
	No	46.50	3.873	1.936
moisture %	Yes	5.37	2.426	.410
	No	5.00	1.414	.707
silt 2%	Yes	38.71	9.167	1.550
	No	41.25	4.573	2.287
sand2 %	Yes	26.17	15.890	2.686
	No	12.75	5.058	2.529
AL-P2O5	Yes	13.37	16.380	2.769
	No	2.00	1.826	.913
AL-K2O	Yes	324.80	270.412	45.708
	No	267.50	247.421	123.710
N (NH4-N+NO3-N)	No	32.14	29.014	10.966
	Yes	23.35	21.656	3.126

Minimum tillage and soil properties

Table A 7. Descriptive statistics of Minimum tillage and soil properties

Group Statistics			
Min_tillage	Mean	Std. Deviation	Std. Error Mean

Ca (Cmol/kg)	No	1.579992	.7532179	.1506436
	Yes	2.225461	2.1205144	.3093088
K (Cmol/kg)	No	.589194	.5489508	.1097902
	Yes	.283890	.2732805	.0398621
Mg (Cmol/kg)	No	.637430	.6001788	.1200358
	Yes	.739904	.6808745	.0993158
Na (Cmol/kg)	No	.077061	.0995067	.0199013
	Yes	.043501	.0698067	.0101824
pH(H2O)	No	5.627	.4635	.0909
	Yes	5.410	.9690	.1344
pH(HCL)	No	4.519	.3487	.0684
	Yes	4.583	.7329	.1016
OC	No	.90142	.413477	.084401
	Yes	1.36606	1.214874	.173553
CEC	No	16.39296	5.425793	1.085159
	Yes	19.98332	9.629970	1.361883
BS %	No	18.40617	9.940782	2.029154
	Yes	17.32417	13.265099	1.955832
Clay %	Yes	36.92	13.437	2.635
	No	35.46	12.183	3.379
moisture %	Yes	5.15	2.148	.421
	No	5.69	2.720	.754
silt 2%	Yes	39.12	9.820	1.926
	No	38.69	6.651	1.845
sand2 %	Yes	24.23	16.296	3.196
	No	25.92	14.846	4.118
AL-P2O5	Yes	15.81	17.659	3.463
	No	5.00	8.103	2.248
AL-K2O	Yes	281.38	264.830	51.937
	No	394.00	261.137	72.426
N (NH4-N+NO3-N)	No	20.73	23.131	4.932
	Yes	26.97	22.231	3.870

Mulching and soil properties

Table A 8. Descriptive statistics of Mulching and soil properties

Group statistics				
Mulching		Mean	Std. Deviation	Std. Error Mean
Ca (Cmol/kg)	No	1.378842	1.2825731	.3206433
	Yes	2.179196	1.8810616	.2513674
K (Cmol/kg)	No	.364248	.3135317	.0783829
	Yes	.397227	.4410894	.0589431
Mg (Cmol/kg)	No	.505883	.3494121	.0873530
	Yes	.761020	.7071101	.0944916
Na (Cmol/kg)	No	.125095	.0975597	.0243899
	Yes	.035171	.0656126	.0087678
pH(H2O)	No	5.256	.6600	.1556
	Yes	5.550	.8779	.1133
pH(HCL)	No	4.294	.5330	.1256
	Yes	4.642	.6379	.0823
OC	No	1.19475	.638881	.159720
	Yes	1.21851	1.134875	.150318
CEC	No	16.20450	5.005202	1.251301
	Yes	19.48675	9.242040	1.203211
BS %	No	16.51986	10.673906	2.852721
	Yes	17.98896	12.580172	1.681096
Clay %	Yes	36.17	12.385	2.261
	No	37.33	15.232	5.077
moisture %	Yes	5.20	2.235	.408
	No	5.78	2.728	.909
silt 2%	Yes	38.53	9.630	1.758
	No	40.44	5.341	1.780
sand2 %	Yes	25.53	15.208	2.777
	No	22.33	17.783	5.928
AL-P2O5	Yes	14.40	16.909	3.087
	No	4.89	9.212	3.071
AL-K2O	Yes	320.13	253.453	46.274
	No	314.89	319.861	106.620
N (NH4-N+NO3-N)	No	16.45	9.213	2.778
	Yes	26.48	24.511	3.695

Crop residue application and soil properties

Table A 9. Descriptive statistics of Crop residue application and soil properties

Group statistics

Residue		Mean	Std. Deviation	Std. Error Mean
Ca (Cmol/kg)	No	1.900317	2.0222795	.3238239
	Yes	2.120730	1.4893817	.2592681
K (Cmol/kg)	No	.388667	.3858127	.0617795
	Yes	.391353	.4518149	.0786509
Mg (Cmol/kg)	No	.737811	.7566958	.1211683
	Yes	.664746	.5089166	.0885910
Na (Cmol/kg)	No	.088027	.0957602	.0153339
	Yes	.016304	.0352506	.0061363
pH(H2O)	No	5.536	.7622	.1176
	Yes	5.419	.9258	.1543
pH(HCL)	No	4.586	.6031	.0931
	Yes	4.533	.6663	.1111
OC	No	1.02225	.699817	.110651
	Yes	1.44488	1.321984	.230128
CEC	No	16.71390	6.967599	1.101674
	Yes	21.15526	9.707342	1.640840
BS %	No	18.37727	12.916440	2.123450
	Yes	16.93033	11.411444	1.986478
Clay %	Yes	33.61	13.971	3.293
	No	38.86	11.680	2.549
moisture %	Yes	4.67	1.680	.396
	No	5.90	2.682	.585
silt 2%	Yes	38.72	9.177	2.163
	No	39.19	8.687	1.896
sand2 %	Yes	27.83	15.957	3.761
	No	22.19	15.283	3.335
AL-P2O5	Yes	16.56	19.536	4.605
	No	8.48	11.125	2.428
AL-K2O	Yes	307.33	243.174	57.317
	No	328.86	289.123	63.092
N (NH4-N+NO3-N)	No	27.21	24.791	4.316
	Yes	20.36	18.618	3.969

Type of farming and soil properties

Table A 10. Descriptive statistics of farming type and soil properties

Group statistics				
FarmType		Mean	Std. Deviation	Std. Error Mean
Ca (Cmol/kg)	Crops	.943800	1.1741508	.8302500
	Crops and Livestock	2.031555	1.8000752	.2151501
K (Cmol/kg)	Crops	.167615	.0076150	.0053846

	Crops and Livestock	.396249	.4185406	.0500252
Mg (Cmol/kg)	Crops	.056375	.0121976	.0086250
	Crops and Livestock	.722836	.6513959	.0778567
Na (Cmol/kg)	Crops	.037174	.0175240	.0123913
	Crops and Livestock	.055668	.0833364	.0099606
pH(H2O)	Crops	5.850	.2121	.1500
	Crops and Livestock	5.472	.8466	.0971
pH(HCL)	Crops	4.200	.1414	.1000
	Crops and Livestock	4.571	.6347	.0728
OC	Crops	.93100		
	Crops and Livestock	1.21722	1.049302	.123661
CEC	Crops	19.71000	6.482755	4.584000
	Crops and Livestock	18.76123	8.677628	1.015640
BS %	Crops	7.53150	8.623167	6.097500
	Crops and Livestock	17.99407	12.169571	1.475777
Clay %	Crop Farming	34.00		
	Crop and livestock farming	36.50	13.057	2.118
moisture %	Crop Farming	4.00		
	Crop and livestock farming	5.37	2.353	.382
silt 2%	Crop Farming	35.00		
	Crop and livestock farming	39.08	8.894	1.443
sand2 %	Crop Farming	31.00		
	Crop and livestock farming	24.63	15.827	2.568
AL-P2O5	Crop Farming	30.00		
	Crop and livestock farming	11.74	15.830	2.568
AL-K2O	Crop Farming	173.00		
	Crop and livestock farming	322.76	268.114	43.494
Clay %	Yes	36.18	12.965	2.103
	No	46.00		
moisture %	Yes	5.29	2.347	.381

	No	7.00		
silt 2%	Yes	39.03	8.912	1.446
	No	37.00		
sand2 %	Yes	24.97	15.821	2.566
	No	18.00		
AL-P2O5	Yes	12.05	16.076	2.608
	No	18.00		
AL-K2O	Yes	322.89	268.037	43.481
	No	168.00		
N (NH4-N+NO3-N)	Crop farming	13.00	2.646	1.528
	Crop and Livestock	24.20	21.608	3.056

Land use and soil properties

Table A 11. Descriptive statistics of land use and soil properties

No.	Soil attribute	Land use	Mean	Std. Dev	P-value
1	BS	Banana	20.12943	11.21438	
		Coffee	18.22779	15.41061	
		Legumes	23.14823	10.08371	
		Maize	17.90177	12.83921	
		Pasture			
		Tea	10.43864	8.038236	0.1079
2	CEC	Banana	19.13348	4.644148	
		Coffee	14.62617	5.415283	
		Legumes	18.22368	5.79166	
		Maize	19.81957	11.05599	
		Pasture	10.70919		
		Tea	18.528	3.616527	0.1079
3	Exch. Ca	Banana	2.92573	1.315804	
		Coffee	1.330114	1.143617	
		Legumes	2.4833	0.680626	
		Maize	2.111925	2.173575	
		Pasture	1.86405	N/A	
		Tea	0.891771	0.804828	0.115
4	Exch. K	Banana	0.531913	0.654496	
		Coffee	0.485549	0.32429	
		Legumes	0.439346	0.12221	
		Maize	0.32058	0.398558	
		Pasture	0.086077		
		Tea	0.414521	0.326702	0.662
5	Exch. Mg	Banana	0.817091	0.372684	
		Coffee	0.497321	0.645783	
		Legumes	0.878458	0.396684	
		Maize	0.810163	0.787982	0.227

		Pasture	0.63875		
		Tea	0.287875	0.281888	
6	Exch. Na	Banana	0.012925	0.028099	
		Coffee	0.010621	0.019499	
		Legumes	0.04	0.064496	
		Maize	0.054167	0.075792	
		Pasture	0.310435		
		Tea	0.114012	0.104861	0.000354
7	pH (H_2O)	Banana	5.908333	0.883648	
		Coffee	5.8125	0.479397	
		Legumes	5.916667	0.213698	
		Maize	5.378947	0.869034	
		Pasture	5.45	0.070711	
		Tea	4.975	0.760532	0.00156
8	pH (HCl)	Banana	4.958333	0.737882	
		Coffee	4.8125	0.754865	
		Legumes	4.716667	0.183485	
		Maize	4.526316	0.575952	
		Pasture	4	0	
		Tea	4.125	0.484534	0.0122
9	OC	Banana	1.019182	0.439534	
		Coffee	0.855446	0.343845	
		Legumes	0.8984	0.132187	
		Maize	1.281741	1.401837	
		Pasture			
		Tea	1.568048	0.516375	0.005716
10	Tot N	Banana	12.5	4.907817	
		Coffee	15.22857	8.301348	
		Legumes	9.733333	2.386071	
		Maize	16.84091	13.59197	
		Pasture	17.9		
		Tea	46.28	30.18934	
		Potatoes	20.7		
		Vegetables	28.2	5.091169	0.00154
11	Phosphorus	Banana	15.96417	20.55407	
		Coffee	22.075	8.901077	
		Legumes	9.133333	7.985821	
		Maize	9.663789	16.20782	
		Pasture	0.709		
		Tea	13.465	17.59381	0.716
12	K(extract.)	Banana	321.0567	252.8001	
		Coffee	451	401.7487	
		Legumes	441.3333	200.4029	
		Maize	260.6263	235.6922	
		Pasture	66.8		
		Tea	394.3	322.5577	0.585

13	Clay	Banana	27.31408	17.24254	
		Coffee	41.46801	12.63318	
		Legumes	28.57679	2.181857	
		Maize	39.23703	10.22545	
		Pasture	47.59369		
		Tea	34.84594	16.36009	0.263
14	Silt	Banana	38.83208	10.36155	
		Coffee	36.75125	7.196069	
		Legumes	43.36917	13.00517	
		Maize	38.04816	9.329499	
		Pasture	35.685		
		Tea	41.46917	6.101505	0.887
15	Sand	Banana	33.85384	15.49394	
		Coffee	21.78074	19.72472	
		Legumes	28.05405	15.17741	
		Maize	22.71481	14.2049	
		Pasture	16.72131		
		Tea	23.68489	20.79686	0.739
16	Moisture	Banana	4.042541	0.735527	
		Coffee	5.636051	2.78392	
		Legumes	4.411371	0.762496	
		Maize	5.3465	2.238825	
		Pasture	3.837294		
		Tea	6.995761	3.040629	0.296

Appendix F Soil pH interpretation

Table A 12. Soil pH Threshold values

pH	**Rating**
<4.5	Extremely acid
4.5-5.0	Very strongly acid
5.1-5.5	Strongly acid
5.6-6.0	Medium acid
6.1-6.5	Slightly acid
6.6-7.3	Neutral
7.4-7.8	Mildly alkaline

7.9-8.4	Moderately alkaline
8.5-9.0	Strongly alkaline
>9.0	Very strongly alkaline

(Wanjogu et al., 2001)..page 6

Appendix G Rating Organic carbon

Table A 13. SOC Threshold values

% OC	Rating
<1.2	Low
1.2-2.0	Moderate
>2.0	High

Appendix H SOIL CLASSIFICATION

Table A 14. Results of soil properties, soil classification and the generated Reference soil groups

S/n	Farm	Up_d	Low_d	SOC	CEC.	Bs.	pH.	Sand.	Silt.	Clay.	Text	Soil	MOIST-Munsel	WRB Diagn	WRB RSG	WRB soil name
1	F001	0	20	0.49	9.67	13.68	4.8	18.53	42.46	39.01	SiCL	Loam	2.5YR3/6	Umbric, Argic, Nitic, Andic	Nitisol	Rhodic Umbric Acric Systric Nitisol Andic Aric
2	F001	20	50	0.47	9.64	15.24	5.1	17.99	42.73	39.27	SiCL	Loam	2.5YR2.5/4			
3	F001	50	100	0.67	9.63	17.06	5.4	20.01	41.51	38.48	CL	Loam	10R3/4			
4	F002	0	20	0.51	9.63	10.56	4.2	34.01	33.55	32.44	CL	Loam	5YR3/4	Umbric, Argic, Nitic	Nitisol	Umbric Acric Dystric Nitisol Aric
5	F002	20	50	0.49	9.61	10.82	4.2	18.4	42.61	38.98	SiCL	Loam	2.5YR4/4			
6	F002	50	100	0.57	12.96	14.98	5	22.75	39.98	37.27	CL	Loam	10R3/3			
7	F003	0	20		3.81	20.96	6.2	33.91	33.33	32.76	CL	Loam	2.5YR2.5/4	Cambic	Cambisol	Dystric Cambisol Aric Escalic Ochric
8	F003	20	50	2.98	3.17	22.78	6.5	34.33	33.04	32.63	CL	Loam	5YR3/4			
9	F003	50	100	3.58	2.16	23.3	6.6	30.66	35.16	34.18	CL	Loam	2.5YR2.5/3			
10	F004	0	20	0.56	9.6	22.78	6.5	37.34	31.29	31.37	CL	Loam	5YR3/4	Umbric, Argic, Nitic	Nitisol	Umbric Acric Dystric Nitisol Aric
11	F004	20	50	0.48	9.57	23.56	6.7	36.77	31.6	31.63	CL	Loam	5YR3/3			
12	F004	50	100	0.74	9.55	24.6	6.9	31.76	34.48	33.76	CL	Loam	7.5YR2.5/2			
13	F005	0	20	0.62	9.54	22.26	6.4	50.23	23.81	25.96	SCL	Loam	2.5YR2.5/4	Umbric, Argic, Nitic, Andic	Nitisol	Umbric, Acric, Dystric Nitisol, Aric, Andic
14	F005	20	50	0.76	12.78	23.04	6.6	45.94	26.28	27.78	SCL	Loam	2.5YR2.5/3			
15	F005	50	100	1.24	9.51	23.56	6.7	39.48	30.03	30.5	CL	Loam	5YR3/4			
16	F006	0	20	0.8	9.5	20.44	6.1	34.66	32.91	32.43	CL	Loam	7.5R3/3	Umbric, Argic, Nitic, Andic	Nitisol	Umbric, Acric, Dystric Nitisol, Aric, Andic
17	F006	20	50	1.24	11.75	19.92	6	32.43	34.22	33.35	CL	Loam	2.5YR2.5/4			
18	F006	50	100		11.16	18.62	5.7	28.13	36.75	35.12	CL	Loam	2.5YR2.5/3			
19	F007	0	20	0.52	9.49	12.12	4.5	25.06	38.71	36.23	CL	Loam	10R3/6	Argic, Nitic, Andic	Nitisol	Acric, Nitisol, Andic, Aric, Ochric
20	F007	20	50	0.53	9.46	10.82	4.2	14.56	44.85	40.59	SiC	Clay	2.5YR2.5/3			
21	F007	50	100	0.48	9.44	13.42	4.7	16.69	43.54	39.77	SiCL	Loam	2.5YR2.5/4			
22	F008	0	20	0.26	11.09	15.5	5.1	19.61	41.78	38.6	SiCL	Loam	2.5YR3/4	Argic, Nitic	Nitisol	Rhodic Acric Dystric Nitisol Ochric
23	F008	20	50	0.76	10.98	16.8	5.4	17.73	42.84	39.42	SiCL	Loam	10R3/4			
24	F008	50	100	0.51	9.43	17.32	5.5	16.25	43.69	40.06	SiC	Clay	2.5YR3/4			
25	F009	0	20	0.9	9.42	17.06	5.4	25.89	38.1	36.02	CL	Loam	10R3/3	Argic, Nitic	Nitisol	

S/n	Farm	Up_d	Low_d	SOC	CEC.	Bs.	pH.	Sand.	Silt.	Clay.	Text	Soil	MOIST-Munsel	WRB Diagn	WRB RSG	WRB soil name
26	F009	20	50	1.36	9.41	18.36	5.7	23.19	39.63	37.18	CL	Loam	2.5YR2.5/4			Rhodic Acric Dystric Nitisol Aric Ochric
27	F009	50	100	0.65	9.41	17.32	5.5	18.49	42.39	39.12	SiCL	Loam	2.5YR3/4			
28	F010	0	20	1.01	9.4	13.16	4.7	19.85	41.71	38.44	SiCL	Loam	2.5YR2.5/4	Argic, Nitic, Colluvic mat	Nitisol	Acric Dystric Nitisol Aric Colluvic Ochric
29	F010	20	50	1.37	9.39	13.94	4.8	19.74	41.75	38.51	SiCL	Loam	2.5YR2.5/4			
30	F010	50	100	0.8	9.3	13.42	4.7	14.1	45.04	40.85	SiC	Clay	5YR4/6			
31	F011	0	20	0.14	9.28	18.62	5.7	29.09	36.2	34.72	CL	Loam	10R3/4	Argic	Acrisol	Endoskeletic Acrisol Aric Cutanic Ochric
32	F011	20	50	0.38	9.26	20.18	6	24.87	38.6	36.52	CL	Loam	7.5YR2.5/2			
33	F011	50	100	0.92	9.25	19.66	5.9	21.74	40.44	37.82	CL	Loam	2.5YR4/4			
34	F012	0	20	1.51	9.24	18.1	5.6	25.91	38.06	36.03	CL	Loam	10R3/4	Umbric, Argic, Nitic	Nitisol	Umbric, Acric Dystric Nitisol Aric
35	F012	20	50	0.65	9.23	15.5	5.1	21.79	40.52	37.69	CL	Loam	2.5YR2.5/4			
36	F012	50	100	1.19	9.22	16.02	5.2	16.81	43.4	39.79	SiCL	Loam	7.5YR2.5/2			
37	F013	0	20	0.59	9.21	15.24	5.1	21.54	40.67	37.79	CL	Loam	10R3/3	Umbric, Argic, Nitic	Nitisol	Umbric, Acric Dystric Nitisol Aric
38	F013	20	50	0.9	9.17	15.24	5.1	19.74	41.72	38.54	SiCL	Loam	5YR3/4			
39	F013	50	100	0.87	9.16	17.06	5.4	17.85	42.77	39.38	SiCL	Loam	2.5YR2.5/4			
40	F014	0	20	1.42	9.15	15.76	5.2	19.67	41.75	38.59	SiCL	Loam	10R3/4	Argic, Nitic	Nitisol	Rhodic Acric Dystric Nitisol Aric Ochric
41	F014	20	50	0.94	9.15	16.02	5.2	16.78	43.42	39.8	SiCL	Loam	5YR3/4			
42	F014	50	100	0.32	10.89	15.76	5.2	14.63	44.68	40.7	SiC	Clay	2.5YR3/6			
43	F015	0	20	1.01	9.14	14.98	5	19.25	42.01	38.74	SiCL	Loam	2.5YR2.5/4	Umbric, Argic	Acrisol	Umbric Dystric Acrisol
44	F015	20	50	0.95	9.14	16.28	5.3	15.58	44.11	40.31	SiC	Clay	2.5YR2.5/3			
45	F015	50	100	1.37	9.14	17.06	5.4	17.7	42.85	39.44	SiCL	Loam	2.5YR2.5/3			
46	F016	0	20	1.12	9.12	20.7	6.1	27.42	37.11	35.47	CL	Loam	2.5YR2.5/3	Umbric, Argic, Nitic	Nitisol	Umbric Acric Dystric Nitisol Aric
47	F016	20	50	0.74	9.1	19.66	5.9	23.65	39.33	37.02	CL	Loam	2.5YR3/4			
48	F016	50	100	0.33	10.82	17.32	5.5	19.48	41.81	38.71	SiCL	Loam	7.5YR2.5/1			
49	F017	0	20	1.23	9.08	17.06	5.4	20.6	41.17	38.23	CL	Loam	2.5YR2.5/4	Argic, Nitic	Nitisol	Acric Dystric Nitisol Aric Ochric
50	F017	20	50	0.71	9.03	17.84	5.6	19.62	41.72	38.66	SiCL	Loam	7.5YR2.5/2			
51	F017	50	100	0.14	10.62	20.7	6.1	22.76	39.82	37.42	CL	Loam	2.5YR3/3			
52	F018	0	20	0.43	10.62	18.88	5.8	20.79	41.01	38.2	CL	Loam	5YR3/3	Umbric, Argic, Nitic, Protovertic	Nitisol	Rhodic, Umbric, Acric, Dystric Nitisol Aric Humic
53	F018	20	50	0.54	9	18.88	5.8	21.59	40.54	37.86	CL	Loam	10R3/3			
54	F018	50	100	0.61	8.98	19.4	5.9	24.38	38.91	36.71	CL	Loam	7.5YR3/2			

S/n	Farm	Up_d	Low_d	SOC	CEC.	Bs.	pH.	Sand.	Silt.	Clay.	Text	Soil	MOIST-Munsel	WRB Diagn	WRB RSG	WRB soil name
55	F019	0	20	1.61	8.98	14.98	5	18.19	42.62	39.18	SiCL	Loam	7.5R3/2	Argic, Nitic	Nitisol	Acric Dystric Nitisol Aric Ochric
56	F019	20	50	0.81	8.97	15.5	5.1	17.65	42.93	39.42	SiCL	Loam	2.5YR2.5/4			
57	F019	50	100	0.49	8.96	16.54	5.3	17.48	43	39.52	SiCL	Loam	2.5YR4/6			
58	F020	0	20	0.6	8.95	16.54	5.3	17.83	42.8	39.38	SiCL	Loam	10R3/4	Umbric, Argic, Nitic	Nitisol	Rhodic Umbric Acric Dystric Nitisol Acric Humic
59	F020	20	50	0.57	8.94	16.54	5.3	16.58	43.52	39.9	SiCL	Loam	10R3/3			
60	F020	50	100	0.89	8.93	16.54	5.3	16.07	43.81	40.11	SiC	Clay	10R3/3			
61	F021	0	20	1.42	8.91	19.92	6	25.78	38.08	36.14	CL	Loam	2.5YR2.5/4	Umbric, Argic, Nitic, Colluvic mat	Nitisol	Umbric, Acric Nitisol Aric Colluvic
62	F021	20	50	0.52	8.9	16.02	5.2	14.9	44.51	40.59	SiC	Clay	5YR4/6			
63	F021	50	100	0.63	8.89	15.76	5.2	13.41	45.38	41.21	SiC	Clay	7.5YR3/2			
64	F022	0	20	0.88	10.49	19.66	5.9	28.56	36.47	34.96	CL	Loam	2.5YR2.5/3	Argic, Pisoplinthic	Acrisol	Pisoplinthic Acrisol Aric Humic
65	F022	20	50	0.65	8.78	15.76	5.2	19.06	42.1	38.84	SiCL	Loam	2.5YR2.5/4			
66	F022	50	100	0.69	8.76	16.28	5.3	16.43	43.62	39.96	SiCL	Loam	10R3/2			
67	F023	0	20	0.6	8.74	16.54	5.3	20.73	41.11	38.16	CL	Loam	7.5YR4/2	Pisoplinthic	Plinthosol	Pisoplinthic Plinthosol Aric
68	F023	20	50	0.67	8.74	15.24	5.1	19.69	41.75	38.56	SiCL	Loam	2.5YR3/3			
69	F023	50	100	1.76	8.72	17.84	5.6	18.6	42.31	39.09	SiCL	Loam	10R3/6			
70	F024	0	20	1.16	8.72	26.94	7.3	32.95	33.73	33.32	CL	Loam	10R3/3	Argic, Pisoplinthic	Acrisol	Pisoplinthic Acrisol Aric Humic
71	F024	20	50	1.58	8.71	26.42	7.2	30.45	35.2	34.35	CL	Loam	10R3/3			
72	F024	50	100	0.47	8.69	23.3	6.6	24.02	39.02	36.96	CL	Loam	10R3/3			
73	F025	0	20	0.57	8.68	23.04	6.6	29.66	35.74	34.59	CL	Loam	5YR3/4	Argic	Acrisol	Chromic Acrisol Cutanic Ochric
74	F025	20	50	0.74	8.67	20.44	6.1	23.13	39.61	37.26	CL	Loam	2.5YR3/6			
75	F025	50	100	1.15	8.67	20.44	6.1	23.83	39.2	36.97	CL	Loam	10R3/4			
76	F026	0	20	0.93	8.66	23.04	6.6	28.85	36.21	34.93	CL	Loam	2.5YR2.5/4	Cambic	Cambisol	Rhodic Dystric Cambisol Aric Ochric
77	F026	20	50	2.01	8.63	24.08	6.8	30.02	35.51	34.47	CL	Loam	10R2.5/2			
78	F026	50	100	0.8	8.61	20.96	6.2	22.72	39.83	37.44	CL	Loam	10R3/6			
79	F027	0	20	1.09	8.6	23.56	6.7	30.18	35.43	34.39	CL	Loam	2.5YR2.5/3	Argic	Acrisol	Rhodic Acrisol Aric Cutanic Ochric
80	F027	20	50	0.94	8.58	23.56	6.7	26.55	37.54	35.91	CL	Loam	5YR4/4			
81	F027	50	100	1.92	8.55	20.18	6	22.02	40.26	37.72	CL	Loam	2.5YR2.5/4			
82	F028	0	20	0.53	10.42	18.62	5.7	22.25	40.17	37.58	CL	Loam	2.5YR2.5/3	Argic	Acrisol	
83	F028	20	50	0.55	8.53	19.66	5.9	22.88	39.78	37.34	CL	Loam	2.5YR3/6			

S/n	Farm	Up_d	Low_d	SOC	CEC.	Bs.	pH.	Sand.	Silt.	Clay.	Text	Soil	MOIST-Munsel	WRB Diagn	WRB RSG	WRB soil name
84	F028	50	100	0.43	8.52	20.96	6.2	22.04	40.23	37.73	CL	Loam	10R3/4			Rhodic Acrisol Aric Cutanic Ochric
85	F029	0	20	0.59	8.52	22.26	6.4	27.14	37.23	35.63	CL	Loam	2.5YR2.5/4	Argic	Acrisol	Rhodic Chromic? Acrisol Cutanic Ochric
86	F029	20	50	1.79	8.49	21.74	6.3	26.1	37.85	36.05	CL	Loam	2.5YR4/8			
87	F029	50	100	0.61	10.39	21.74	6.3	23.43	39.4	37.17	CL	Loam	2.5YR2.5/4			
88	F030	0	20	0.28	10.34	19.92	6	25.57	38.2	36.22	CL	Loam	10R3/4	Umbric, Argic, Nitic	Nitisol	Rhodic, Umbric, Acric, Dystric Nitisol Aric
89	F030	20	50	1.18	8.48	18.88	5.8	21.05	40.86	38.09	CL	Loam	7.5YR2.5/2			
90	F030	50	100	0.74	8.48	19.66	5.9	20.78	41	38.22	CL	Loam	2.5YR2.5/3			
91	F031	0	20	0.84	8.47	20.18	6	29.24	36.06	34.69	CL	Loam	2.5YR2.5/4	Umbric, Argic, Nitic	Nitisol	Umbric, Acric, Dystric Nitisol Aric
92	F031	20	50	0.58	10.31	19.66	5.9	25.35	38.34	36.31	CL	Loam	2.5YR2.5/4			
93	F031	50	100	0.88	10.3	20.18	6	23.42	39.45	37.13	CL	Loam	2.5YR3/6			
94	F032	0	20	1.33	8.43	25.38	7	34.05	33.13	32.82	CL	Loam	2.5YR2.5/3	Umbric, Argic, Nitic	Nitisol	Umbric, Acric, Dystric Nitisol Aric
95	F032	20	50	0.66	8.43	25.64	7.1	31.74	34.47	33.79	CL	Loam	2.5YR2.5/4			
96	F032	50	100	0.92	10.28	25.38	7	29.8	35.6	34.6	CL	Loam	2.5YR2.5/1			
97	F033	0	20	0.77	8.41	22	6.4	22.83	39.74	37.43	CL	Loam	10R3/4	Argic, Nitic+P98:R98	Nitisol	Acric, Dystric Nitisol Aric
98	F033	20	50	1.86	8.41	20.7	6.1	23.28	39.51	37.2	CL	Loam	2.5YR3/4			
99	F033	50	100	0.65	8.4	19.92	6	25.42	38.29	36.29	CL	Loam	2.5YR3/4			
100	F034	0	20	0.28	10.28	18.62	5.7	20.66	41.09	38.25	CL	Loam	2.5YR2.5/4	Umbric, Argic, Nitic, Colluvic mat	Nitisol	Umbric, Acric, Dystric Nitisol Aric Colluvic Humic
101	F034	20	50	0.94	8.38	19.4	5.9	19.5	41.75	38.75	SiCL	Loam	2.5YR2.5/4			
102	F034	50	100	0.53	8.38	19.14	5.8	21.52	40.58	37.9	CL	Loam	2.5YR3/3			
103	F035	0	20	0.73	8.36	23.82	6.7	29.93	35.57	34.5	CL	Loam	7.5YR3/2	Umbric, Argic, Nitic, Gleyic prop	Gleysol	Umbric Reductigleyic Dystric Gleysol Acric Aric Colluvic Humic
104	F035	20	50	0.83	8.3	23.56	6.7	26.81	37.39	35.8	CL	Loam	10R3/3			
105	F035	50	100	0.87	10.25	20.18	6	24.4	38.88	36.72	CL	Loam	2.5YR3/2			
106	F036	0	20	0.75	8.27	19.14	5.8	21.71	40.47	37.82	CL	Loam	7.5YR2.5/2	Argic, Nitic	Nitisol	Acric, Dystric Nitisol Aric
107	F036	20	50	1.11	10.23	21.22	6.2	19.52	41.69	38.79	SiCL	Loam	2.5YR2.5/4			
108	F036	50	100	0.39	8.26	19.14	5.8	17.07	43.16	39.76	SiCL	Loam	2.5YR2.5/3			
109	F037	0	20	1.09	8.22	15.5	5.1	24.35	39.03	36.62	CL	Loam	2.5YR3/3	Umbric,Argic, Nitic	Nitisol	
110	F037	20	50	0.85	8.19	14.46	4.9	18.5	42.46	39.04	SiCL	Loam	2.5YR2.5/3			

S/n	Farm	Up_d	Low_d	SOC	CEC.	Bs.	pH.	Sand.	Silt.	Clay.	Text	Soil	MOIST-Munsel	WRB Diagn	WRB RSG	WRB soil name
111	F037	50	100	0.85	10.16	15.24	5.1	17.17	43.21	39.62	SiCL	Loam	2.5YR3/2			Rhodic, Acric, Dystric Nitisol Aric
112	F038	0	20	0.66	8.18	17.58	5.5	20.35	41.3	38.35	CL	Loam	7.5R2.5/3	Argic, Nitic, Gleyic prop, Reducing cond	Nitisol	Acric Dystric Nitisol Aric Endogleyic Ochric
113	F038	20	50	2.19	8.14	16.02	5.2	22.65	40.01	37.35	CL	Loam				
114	F038	50	100	0.85	8.13	14.98	5	26.01	38.08	35.91	CL	Loam	10R3/3			
115	F039	0	20	0.95	8.12	11.86	4.4	21.38	40.85	37.77	CL	Loam	10R3/4	Cambic, Colluvic mat	Cambisol	Dystric Cambisol Aric Colluvic Ochric
116	F039	20	50	0.95	8.11	12.38	4.5	20.55	41.32	38.13	CL	Loam	7.5R2.5/3			
117	F039	50	100	1.45	8.07	12.9	4.6	19.23	42.07	38.69	SiCL	Loam	10R2.5/2			
118	F040	0	20	0.9	8.02	10.56	4.2	20.15	41.6	38.25	CL	Loam	10R5/2	Argic, Nitic	Nitisol	Acric, Dystric Nitisol Aric
119	F040	20	50	0.77	8.02	10.82	4.2	22.62	40.16	37.22	CL	Loam	2.5YR3/4			
120	F040	50	100	0.39	10.13	9.26	3.9	23.66	39.6	36.74	CL	Loam	7.5YR2.5/2			
121	F041	0	20	0.33	10.12	17.32	5.5	21.92	40.39	37.68	CL	Loam	5YR3/3	Gleyic prop, Reducing cond	Gleysol	Dystric Gleysol Ochric
122	F041	20	50	1.01	8	15.5	5.1	31.94	34.62	33.44	CL	Loam	10R3/3			
123	F041	50	100	1.02	7.9	18.88	5.8	22	40.31	37.69	CL	Loam	2.5YR2.5/4			
124	F042	0	20	1	7.89	17.32	5.5	18.03	42.66	39.31	SiCL	Loam	10R3/3	Umbric, Argic, Nitic	Nitisol	Umbric, Acric, Dystric Nitisol Aric
125	F042	20	50	1.97	7.86	14.72	5	11.02	46.8	42.18	SiC	Clay	2.5YR2.5/3			
126	F042	50	100	0.59	10.05	17.84	5.6	27.7	43.36	28.93	CL	Loam	10R3/3			
127	F043	0	20	1.04	10.05	19.14	5.8	23.86	39.25	36.88	CL	Loam	10R3/4	Cambic, Colluvic mat	Cambisol	Rhodic Cambisol Aric Colluvic Humic
128	F043	20	50	1.02	7.85	12.12	4.5	27.5	37.29	35.21	CL	Loam	2.5YR2.5/4			
129	F043	50	100	1.04	7.81	18.88	5.8	22.85	39.81	37.34	CL	Loam	2.5YR4/4			
130	F044	0	20	0.84	7.76	18.88	5.8	36.18	32.06	31.75	CL	Loam	2.5YR2.5/4	Argic, Nitic	Nitisol	Acric, Dystric Nitisol Aric
131	F044	20	50	0.35	10.01	11.08	4.3	32.32	34.3	33.38	CL	Loam	2.5YR2.5/4			
132	F044	50	100	1.29	7.75	10.3	4.1	19.01	42.28	38.72	SiCL	Loam	7.5YR2.5/2			
133	F045	0	20	1.43	7.74	7.96	3.7	28.54	36.8	34.66	CL	Loam	10R3/4	Umbric, Argic, Nitic	Nitisol	Umbric, Acric, Dystric Nitisol Aric
134	F045	20	50	0.66	7.68	8.74	3.8	21.54	40.85	37.62	CL	Loam	2.5YR4/3			
135	F045	50	100	1.71	7.68	9	3.9	16.36	43.85	39.79	SiCL	Loam	2.5YR3/4			
136	F046	0	20	1.05	7.66	10.82	4.2	26.7	37.79	35.51	CL	Loam	7.5YR3/4	Umbric, Argic, Nitic	Nitisol	Umbric, Acric, Dystric Nitisol Aric
137	F046	20	50	1.37	7.65	11.34	4.3	19.44	42	38.56	SiCL	Loam	2.5YR2.5/3			
138	F046	50	100	0.61	7.65	11.34	4.3	17.91	42.89	39.21	SiCL	Loam	2.5YR4/4			

S/n	Farm	Up_d	Low_d	SOC	CEC.	Bs.	pH.	Sand.	Silt.	Clay.	Text	Soil	MOIST-Munsel	WRB Diagn	WRB RSG	WRB soil name
139	F047	0	20	0.69	7.62	9.78	4	21.93	40.59	37.48	CL	Loam	2.5YR3/4	Folic, Umbric Andic	Andosol	Folic Umbric Dystric Andosol Aric
140	F047	20	50	0.8	10	9.78	4	22.27	40.36	37.37	CL	Loam	7.5YR3/2			
141	F047	50	100	0.89	7.52	11.86	4.4	19.54	41.92	38.53	SiCL	Loam	2.5YR2.5/4			
142	F048	0	20	0.27	9.98	9.78	4	55.73	20.95	23.33	SCL	Loam	5YR3/4	Umbric, Andic	Andosol	Umbric Dystric Andosol Aric
143	F048	20	50	0.43	9.92	11.86	4.4	31.54	35	33.46	CL	Loam	5YR3/4			
144	F048	50	100	2.34	7.46	12.12	4.5	33.93	33.55	32.52	CL	Loam	7.5R3/3			
145	F049	0	20	0.93	7.44	13.68	4.8	33.86	33.55	32.59	CL	Loam	2.5YR3/2	Umbric, Colluvic, Fluvic	Leptosol	Umbric, Dystric, Leptosol Clayic, Colluvic, Fluvic
146	F049	20	50	5.85	0.7	15.5	5.1						2.5YR2.5/4			
147	F049	50	100			18.88	5.8						2.5YR2.5/4			
148	F050	0	20	1.13	7.44	10.3	4.1	21.21	40.99	37.79	CL	Loam	2.5YR2.5/4	Argic, Nitic	Nitisol	Acric, Dystric Nitisol Aric
149	F050	20	50	1.36	7.42	9.52	4	14.69	44.8	40.5	SiC	Clay	2.5YR2.5/3			
150	F050	50	100	1.36	7.35	9.26	3.9	11.43	46.71	41.86	SiC	Clay	7.5YR3/2			
151	F051	0	20	2.26	7.29	13.94	4.8	17.16	43.25	39.59	SiCL	Loam	2.5YR3/4	Argic	Acrisol	Dystric Acrisol Aric
152	F051	20	50	0.99	7.27	12.9	4.6	15.89	44.02	40.09	SiC	Clay	5YR3/3			
153	F051	50	100	1.48	7.24	13.42	4.7	14.58	44.77	40.65	SiC	Clay	2.5YR2.5/4			
154	F052	0	20	1.23	7.17	16.28	5.3	22.12	40.31	37.57	CL	Loam	2.5YR2.5/4	Argic	Acrisol	Endoleptic Andosol
155	F052	20	50	0.41	9.89	16.28	5.3	18.06	42.67	39.27	SiCL	Loam	2.5YR2.5/3			
156	F052	50	100	1.4	7.15	16.54	5.3	18.66	42.31	39.03	SiCL	Loam	10R3/4			
157	F053	0	20	0.5	9.84	11.08	4.3	14.47	44.89	40.64	SiC	Clay	2.5YR2.5/4	Argic, Colluvic mat	Acrisol	Rhodic Dystric Acrisol Colluvic Cutanic Ochric
158	F053	20	50	1.63	7.15	11.34	4.3	14.72	44.74	40.54	SiCL	Loam	5YR3/4			
159	F053	50	100	0.99	7.14	11.86	4.4	15.12	44.49	40.39	SiCL	Loam	2.5YR3/3			
160	F054	0	20	1.6	7.02	17.84	5.6	28.48	36.57	34.95	CL	Loam	2.5YR2.5/3	Argic	Acrisol	Rhodic Dystric Acrisol Cutanic
161	F054	20	50	1.37	9.83	22.78	6.5	31.35	34.77	33.88	CL	Loam	7.5YR2.5/2			
162	F054	50	100	1.41	7	23.82	6.7	31.29	34.78	33.93	CL	Loam	2.5YR2.5/4			
163	F055	0	20	0.5	9.83	10.82	4.2	18.29	42.68	39.03	SiCL	Loam	2.5YR2.5/4	Argic, Nitic	Nitisol	Acric, Dystric Nitisol Aric
164	F055	20	50	2.92	6.99	10.82	4.2	15.56	44.27	40.18	SiC	Clay				
165	F055	50	100	0.8	6.95	10.3	4.1	13.63	45.4	40.97	SiC	Clay				
166	F056	0	20	1.09	6.95	13.42	4.7	12.38	46.05	41.58	SiC	Clay	2.5YR2.5/3	Argic, Nitic	Nitisol	Acric, Dystric Nitisol Aric
167	F056	20	50	0.83	9.82	12.9	4.6	11.21	46.74	42.05	SiC	Clay	10R3/2			

S/n	Farm	Up_d	Low_d	SOC	CEC.	Bs.	pH.	Sand.	Silt.	Clay.	Text	Soil	MOIST-Munsel	WRB Diagn	WRB RSG	WRB soil name
168	F056	50	100	1.02	6.9	13.16	4.7	12.06	46.23	41.7	SiC	Clay	2.5YR2.5/3			
169	F057	0	20	0.99	6.88	14.46	4.9	15.77	44.05	40.18	SiC	Clay	2.5YR3/3	Cambic	Cambisol	Rhodic Dystric Cambisol Aric Ochric
170	F057	20	50	0.13	9.82	13.42	4.7	13.28	45.52	41.2	SiC	Clay	7.5YR3/2			
171	F057	50	100	1.08	6.84	15.76	5.2	15.53	44.15	40.32	SiC	Clay	10R2.5/2			
172	F058	0	20	0.74	6.82	17.58	5.5	22.32	40.16	37.53	CL	Loam	2.5YR3/2	Umbric, Argic, Colluvic mat	Umbrisol	Acric Cambic Aric Colluvic Rhodic
173	F058	20	50	1.17	6.72	19.14	5.8	20.59	41.12	38.29	CL	Loam	2.5YR3/3			
174	F058	50	100	1.67	6.61	19.66	5.9	21.03	40.85	38.12	CL	Loam	2.5YR3/3			
175	F059	0	20	0.84	9.75	24.08	6.8	26.74	37.42	35.85	CL	Loam	7.5YR3/2	Continous rock	Leptosol	Dystric Leptosol
176	F059	20	50										7.5YR4/2			
177	F059	50	100										7.5YR2.5/2			
178	F060	0	20	1.17	6.58	19.14	5.8	27.67	37	35.32	CL	Loam	2.5YR2.5/4	Continous rock	Leptosol	Dystric Leptosol
179	F060	20	50										2.5YR3/4			
180	F060	50	100										2.5YR3/3			
181	F061	0	20	1.32	6.55	2.24	2.6	7.71	49.06	43.24	SiC	Clay	2.5YR3/3	Cambic, Continous rock	Cambisol	Leptic Dystric Cambisol
182	F061	20	50	1.59	6.52	1.98	2.5	3.24	51.66	45.1	SiC	Clay	5YR3/3			
183	F061	50	100	0.99	6.5	2.76	2.7	2.51	52.06	45.42	SiC	Clay	7.5YR2.5/3			
184	F062	0	20	0.65	9.74	20.96	6.2	28.56	36.44	35	CL	Loam	7.5YR3/3	Pisoplinthic	Plinthosol	Pisoplinthic Plinthosol
185	F062	20	50	1.13	6.48	18.88	5.8	27.36	37.19	35.45	CL	Loam	7.5YR2.5/2			
186	F062	50	100										2.5YR3/2			
187	F063	0	20	3.04	6.32	21.22	6.2	24.94	38.54	36.52	CL	Loam	2.5YR3/6	Argic, Nitic	Nitisol	Acric, Dystric Nitisol Aric
188	F063	20	50	2.34	6.31	19.66	5.9	23.14	39.62	37.23	CL	Loam	7.5YR4/3			
189	F063	50	100	1.9	6.27	16.8	5.4	17.54	42.96	39.5	SiCL	Loam	5YR3/3			
190	F064	0	20	1.82	6.26	17.84	5.6	26.31	37.83	35.86	CL	Loam	2.5YR2.5/4	Argic	Acrisol	Dystric Acrisol Cutanic
191	F064	20	50	0.96	6.24	13.68	4.8	17.03	43.33	39.63	SiCL	Loam				
192	F064	50	100	1.58	6.15	12.9	4.6	14.22	44.99	40.79	SiC	Clay	5YR3/3			
193	F065	0	20	1.6	6.12	14.72	5	19.71	41.75	38.54	SiCL	Loam	7.5YR3/2	Argic	Acrisol	Dystric Acrisol Cutanic
194	F065	20	50	1.29	5.96	19.4	5.9	24.44	38.88	36.68	CL	Loam	7.5YR3/3			
195	F065	50	100			19.14	5.8	20.84	40.97	38.18	CL	Loam	7.5YR3/4			
196	F066	0	20	1.85	5.93	19.66	5.9	30.89	35.12	33.99	CL	Loam	2.5YR2.5/3		Umbrisol	

S/n	Farm	Up_d	Low_d	SOC	CEC.	Bs.	pH.	Sand.	Silt.	Clay.	Text	Soil	MOIST-Munsel	WRB Diagn	WRB RSG	WRB soil name
197	F066	20	50	1.66	5.86	19.4	5.9	24.9	38.61	36.49	CL	Loam	7.5YR2.5/2	Umbric, Argic, Colluvic mat		Acric Cambic Aric Colluvic Rhodic
198	F066	50	100	2.8	5.84	21.48	6.3	24.26	38.93	36.82	CL	Loam	7.5YR2.5/3			
199	F067	0	20	0.82	9.72	20.44	6.1	26.43	37.69	35.88	CL	Loam		Argic	Acrisol	Dystric Acrisol Cutanic
200	F067	20	50	3.01	5.8	19.92	6	24.14	39.04	36.82	CL	Loam				
201	F067	50	100	3.22	5.75	17.58	5.5	18.64	42.3	39.07	SiCL	Loam	7.5YR3/2			
202	F068	0	20	2.01	5.75	20.7	6.1	31.36	34.82	33.82	CL	Loam	7.5YR3/2	Argic	Acrisol	Dystric Acrisol Cutanic
203	F068	20	50	0.51	9.68	22.26	6.4	33.03	33.8	33.16	CL	Loam				
204	F068	50	100	2.39	5.37	22.52	6.5	28.26	36.58	35.17	CL	Loam	2.5YR3/4			
205	F069	0	20	1.85	5.3	22.26	6.4	33.17	33.73	33.1	CL	Loam		Argic	Acrisol	Dystric Acrisol Cutanic
206	F069	20	50	2.01	5.16	22.26	6.4	27.49	37.03	35.48	CL	Loam	2.5YR3/4			
207	F069	50	100		4.68	17.32	5.5	18.36	42.46	39.17	SiCL	Loam				

Table A 15. Correlations of soil properties

		Sand	Silt.	Clay	BS	Exch. K	Mg.	Ca.	Na.	CEC.	AL-K2O	AL.P2O5	pH.	OC.	Moisture
Ava N	Pearson Correlation	$.367^{**}$	$-.350^{**}$	$-.392^{**}$	$-.424^{**}$	-0.081	$-.424^{**}$	$-.381^{**}$	-0.071	0.130	0.138	-0.072	0.082	$-.279^{*}$	0.147
	Sig. (2-tailed)	0.006	0.009	0.003	0.001	0.560	0.001	0.004	0.615	0.343	0.316	0.599	0.554	0.041	0.283
	N	55	55	55	55	54	55	55	53	55	55	55	55	54	55
Sand.	Pearson Correlation		$-.994^{**}$	$-.988^{**}$	$.546^{**}$	$-.152^{*}$	$.546^{**}$	$.353^{**}$	0.020	0.092	$.958^{**}$	$.225^{**}$	$-.165^{*}$	0.017	$.149^{*}$
	Sig. (2-tailed)		0.000	0.000	0.000	0.032	0.000	0.000	0.787	0.196	0.000	0.001	0.020	0.816	0.036
	N		200	200	200	198	200	200	194	200	199	198	199	197	198
Silt.	Pearson Correlation			$.966^{**}$	$-.564^{**}$	$.147^{*}$	$-.564^{**}$	$-.367^{**}$	-0.013	-0.085	$-.965^{**}$	$-.220^{**}$	$.164^{*}$	-0.024	$-.142^{*}$
	Sig. (2-tailed)			0.000	0.000	0.039	0.000	0.000	0.853	0.232	0.000	0.002	0.020	0.733	0.046
	N			200	200	198	200	200	194	200	199	198	199	197	198

Clay.	Pearson Correlation				-.509**	.157*	-.509**	-.325**	-0.028	-0.100	-.948**	-.232**	.164*	-0.005	-.156*
	Sig. (2-tailed)				0.000	0.027	0.000	0.000	0.700	0.159	0.000	0.001	0.021	0.941	0.028
	N				200	198	200	200	194	200	199	198	199	197	198
BS	Pearson Correlation					-.142*	1.000**	.726**	-0.023	0.073	.760**	-0.057	-.205**	0.068	0.122
	Sig. (2-tailed)					0.046	0.000	0.000	0.747	0.306	0.000	0.424	0.004	0.342	0.085
	N					199	202	202	195	201	199	199	201	198	200
Exch. K.	Pearson Correlation						-.142*	-0.101	.209**	-.948**	-.165*	.162*	.760**	.478**	-.941**
	Sig. (2-tailed)						0.046	0.155	0.004	0.000	0.021	0.023	0.000	0.000	0.000
	N						199	199	194	199	197	198	199	198	198
Mg.	Pearson Correlation							.726**	-0.023	0.073	.760**	-0.057	-.205**	0.068	0.122
	Sig. (2-tailed)							0.000	0.747	0.306	0.000	0.424	0.004	0.342	0.085
	N							202	195	201	199	199	201	198	200
Ca.	Pearson Correlation								-0.013	0.057	.514**	-0.069	-0.136	0.028	0.091
	Sig. (2-tailed)								0.860	0.425	0.000	0.335	0.053	0.697	0.198
	N								195	201	199	199	201	198	200
Na.	Pearson Correlation									-.208**	0.006	.182*	0.125	.146*	-.161*
	Sig. (2-tailed)									0.003	0.939	0.011	0.082	0.043	0.025
	N									195	193	194	195	193	194
CEC.	Pearson Correlation										0.094	-.308**	-.510**	-.735**	.956**
	Sig. (2-tailed)										0.188	0.000	0.000	0.000	0.000
	N										199	199	200	198	199
AL-K2O	Pearson Correlation											.156*	-.197**	0.044	.157*
	Sig. (2-tailed)											0.029	0.005	0.544	0.027
	N											198	198	196	197
AL.P2O5.	Pearson Correlation												-.265**	.584**	-.229**
	Sig. (2-tailed)												0.000	0.000	0.001
	N												199	197	198

pH.H2O.	Pearson Correlation													-.194**	-.553**
	Sig. (2-tailed)													0.006	0.000
	N													198	200
SOC.	Pearson Correlation														-.633**
	Sig. (2-tailed)														0.000
	N														197

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Farm household income characteristics

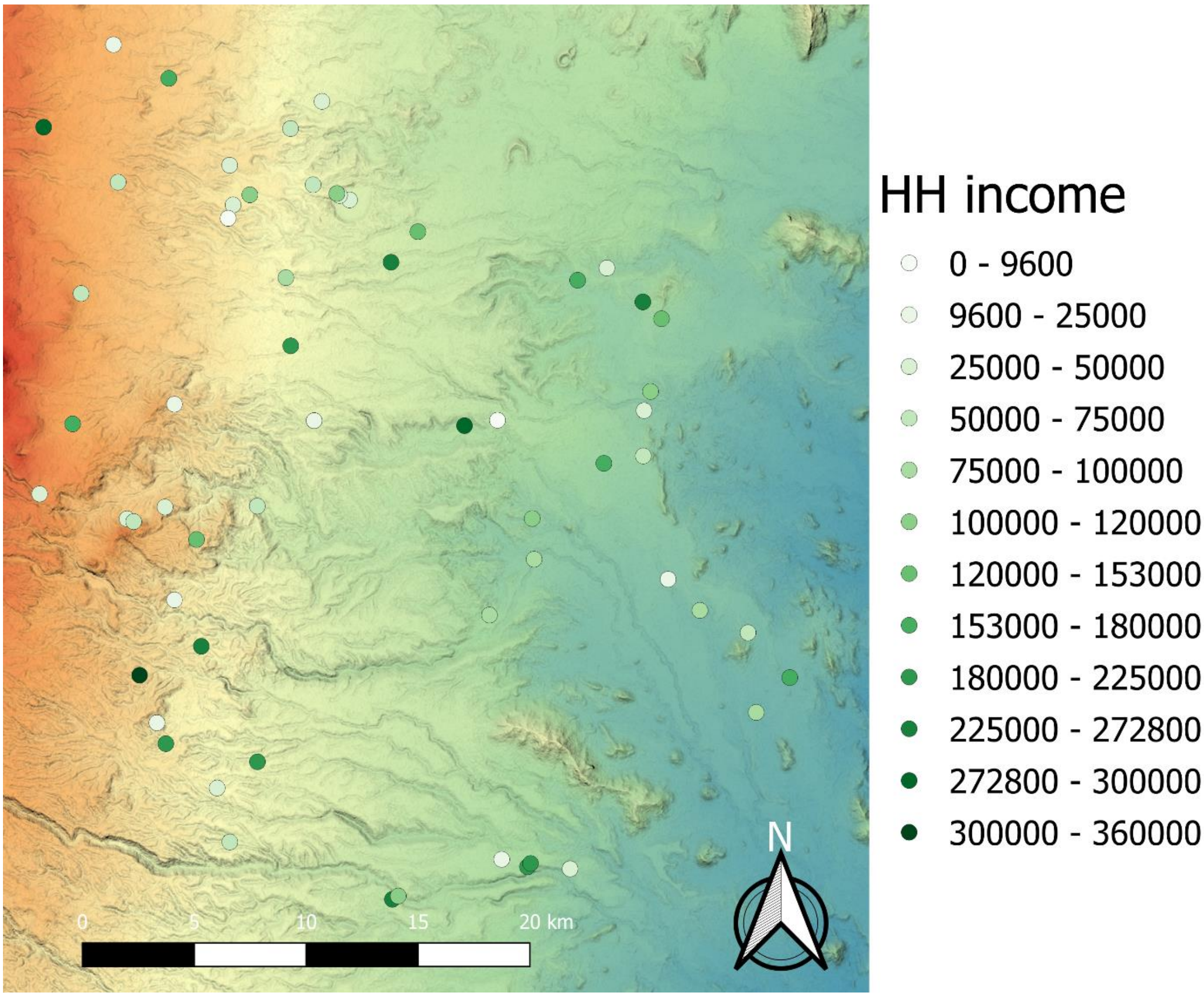

Figure A 1. Income differentiation across farm households