INFLUENCE OF SMALLHOLDER FARMERS' MANAGEMENT PRACTICES ON SOIL ORGANIC CARBON IN WESTERN KENYA

MERCY JEBET KORIR

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE IN SOIL SCIENCE

DEPARTMENT OF LAND RESOURCE MANAGEMENT AND AGRICULTURAL TECHNOLOGY

FACULTY OF AGRICULTURE

UNIVERSITY OF NAIROBI

2021

DECLARATION

This thesis is my original work and has not been submitted for award of a degree in any other University.

Mercy Jebet Korir

A56/8287/2017

Signature …… ………………………….   Date…19/01/2022………

This thesis has been submitted with our approval as the University supervisors.

Prof. Richard Onwonga

Department of Land Resource Management and Agricultural Technology

University of Nairobi

Signature …………………………   Date 07/02/2022 ………………….

Prof. Cecilia M. Onyango

Department of Plant Science and Crop Protection

University of Nairobi

Signature……………………….   Date…02/02/2022…………

Dr. Rolf Sommer

Worldwide Fund for Nature, Berlin, Germany

Signature …………………   Date19/Jan. 2022

DECLARATION OF ORIGINALITY

Name of student: **MERCY JEBET KORIR**

Registration Number: **AF56/8287/2017**

College: **Upper Kabete Campus**

Faculty/School/Institute: **Faculty of Agriculture**

Department: **Department of Land Resource Management and Agricultural Technology**

Course Name: **Master of Science in Soil Science**

Title of the work: **INFLUENCE OF SMALLHOLDER FARMERS' MANAGEMENT PRACTICES ON SOIL ORGANIC CARBON IN WESTERN KENYA**

DECLARATION

1. I understand what Plagiarism is and I am aware of the University's policy in this regard
2. I declare that this **Thesis** (Thesis, project, essay, assignment, paper, report, etc.) is my original work and has not been submitted elsewhere for examination, award of a degree or publication. Where other people's work, or my own work has been used, this has been properly acknowledged and referenced in accordance with the University of Nairobi's requirements.
3. I have not sought or used the services of any professional agencies to produce this work
4. I have not allowed, and shall not allow anyone to copy my work with the intention of passing it off as his/her own work.
5. I understand that any false claim in respect of this work shall result in disciplinary action, in accordance with the University Plagiarism Policy.

Signature ______________________ Date 19thth Jan 2022 ______________________

DEDICATION

This work is dedicated to my father Mr. John Korir, mother Mrs. Sarah Korir and my siblings Gladys, Jacky, Brandon, Naomi, Abby and Kevin for their love and support towards achieving my dream.

ACKNOWLEDGEMENTS

I would like to express my utmost gratitude to my supervisors, Prof. Richard Onwonga, Prof. Cecilia Onyango and Dr. Rolf Sommer for their guidance, advice, encouragement, patience, professional and moral support during this study. I would also like to thank Dr. Sylvia Nyawira of CIAT (International Centre for Tropical Agriculture) for the guidance and support in the use of the CropSyst model used in this study.

Many thanks go to the University of Nairobi and International Centre of Tropical Agriculture (CIAT) for funding this study. This work received financial support from the German Federal Ministry for Economic Cooperation and Development (BMZ) commissioned and administered through the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) Fund for International Agricultural Research (FIA), grant number 81206681. This project was undertaken as part of the CGIAR Research Programs on Water, Land and Ecosystems (WLE).

I am grateful to the farmers in Kakamega and Vihiga for allowing me to conduct interviews and collect soil samples from their fields. Many thanks to the technical support I received from Mr. John Kimotho of University of Nairobi, Mr. Ferdinand Anyika of University of Nairobi and Mr. Francis Mungethu of ILRI (International Livestock and Research Institute, Mazingira for the time spent and guidance given during the analysis of soil and plant samples. I would like to thank Mr. Joshua Mutua of CIAT for the logistical support in the field.

I thank my siblings Gladys, Jacky, Brandon, Naomi, Abby and Kevin for their support and believing in me. Acknowledgements to my friends, Eve, Racheal, Linda and Yunnie for their unwavering support, encouragement and inspiration throughout this journey. To the almighty God, I thank you for the good health, peace of mind, wisdom and guidance.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

FAO: Food and Agriculture Organization

SOC: Soil organic carbon

TOC: Total organic carbon

TON: Total organic nitrogen

BAU: Business-as-usual scenario

CA: Conservation agriculture

GENERAL ABSTRACT

Declining soil organic carbon (SOC) content among smallholder farmers is mainly attributed to different agricultural management practices. A plethora of literature is available on research that has been done on the effect of agricultural management practices on SOC, however, there is limited information on site-specific management practices that improve and sustain carbon content. This study's specific objectives were (i) to assess the predominant agronomic management practices among smallholder farmers and their influence on SOC and potential for sequestration, (ii) to assess the effect of soil physicochemical properties on soil organic carbon and (iii) to simulate SOC dynamics under different management practices using CropSyst model. For the first objective, using secondary data on household surveys from an earlier on-farm survey, a list of farms was generated. Farms with odd numbers and those that had been practicing cultivation for more than 10 years were chosen at a random. A total of 60 farms selected were selected, with 30 farmers selected from Shikomoli (Vihiga) and 30 farms from Mukuyu (Kakamega) villages. Data on land use history, inputs, crop residue retention and soil and water conservation strategies were collected. In addition, soil samples were obtained at consequent depths of 0-20 cm, 20-40 cm and 40-60 cm and analysed for SOC content. Total nitrogen, total organic carbon, silt, clay, sand, pH, available phosphorus, bulk density, exchangeable aluminium, zinc, copper, iron, manganese, and aggregate stability were all analysed in the soil samples for the second objective. For the third objective, the CropSyst model was calibrated and validated with data from farm' fields in Western Kenya and later used to assess soil organic carbon (SOC) sequestration under business-as-usual compared to conservation agriculture. From the 60 farmers identified in the first objective, six farms representing different farmers under maize cropping systems were selected. The main criteria for selection was farms with contrasting soil texture and management practices representing the two sites. The model was calibrated using average farmer reported yields and measured SOC. The calibrated model was then used to project long-term (50 years) SOC trends assuming farm would continue to practice current management practices or, alternatively, conservation agriculture. The results indicated that users of manure in combination with chemical fertilizer were 57% in Shikomoli and 40% in Mukuyu, users of manure combined with crop residue retention and chemical fertilizer were 26% in Shikomoli and 10% in Mukuyu, users of chemical fertilizer alone were 17% in Shikomoli and 33% in Mukuyu and users of chemical fertilizer combined with crop residue retention were 17% in Mukuyu alone.

Hence, in both sites the predominant management practice was manure combined with chemical fertilizer. The key soil and water management techniques used in both sites were trenches and grass strips, with 27 percent in Shikomoli and 64 percent in Mukuyu. Under the combined application of manure, fertilizer, and crop residues, the SOC stock (Mg/ha) content analysis indicated significantly higher carbon stocks in Mukuyu (40.4 Mg/ha) and Shikomoli (29 Mg/ha). The lowest carbon stock resulted from combined application of fertilizer and crop residue in Mukuyu (of 32 Mg/ha) and combined manure and fertilizer application in Shikomoli (22.2 Mg/ha). SOC stocks reduced down the depth in Shikomoli at 0-20 cm depth (26.91 Mg/ha), 20-40 cm (24.17 Mg/ha) and 40-60 cm depth (22.56 Mg/ha) while in Mukuyu at 0-20 cm (40.01 Mg/ha), 20-40 cm (33.83 Mg/ha) and 40-60 cm (30.11 Mg/ha). In Shikomoli and Mukuyu, the 0-20 cm soil depth had the highest soil organic carbon (SOC) stocks (26.9 Mg/ha, 40.01 Mg/ha) while the lowest SOC stocks (22.56 Mg/ha, 30.11 Mg/ha) were observed at 40-60 cm soil depth, respectively. SOC stocks were positively correlated with total nitrogen, carbon to nitrogen ratio, silt, clay, and manganese, while sand and bulk density were negatively correlated with SOC stocks. Under the conventional farmer management practices, SOC stocks decreased for all the farm while under conservation agriculture, SOC stocks increased. Differences in simulated dynamics could be attributed to climatic conditions, soil texture, yield variability, initial carbon content, crop water stress, nitrogen stress and biomass yields. For current farmer management practice, the average annual loss of SOC stocks in the upper 20 cm ranged from 0.03 to 0.19 t C/ha/yr. SOC stocks increased significantly to 0.28 t C/ha/yr after switching to conservation agriculture. The results from this study indicated that loss of SOC stocks among smallholder farming systems could be reversed by adopting management practices that minimized soil disturbance and increase residue retention.

Keywords: soil organic carbon, agricultural management practices, smallholder farmers, CropSyst model, business-as-usual scenario

CHAPTER ONE: INTRODUCTION

1.1 Background

Soils are the largest terrestrial organic pool and mainly governed by the interaction between climate, properties of the soil and agricultural management practices (Yigini and Panagos, 2016; Pan *et al*., 2013). Because of the complex interactions between environment, soil type, and management practices, soil organic carbon (SOC) levels vary widely, particularly among smallholder-farming systems. (Musinguzi *et al.*, 2013). The variations in SOC levels causes a high discrepancy in soil fertility and crop productivity since SOC governs soil health and crop yields (Musinguzi *et al.*, 2013). SOC levels has been on the decline in croplands due to unsustainable management practices leading to soil degradation and nutrient depletion soil (Jackson *et al*., 2017).

Globally, SOC loss of 20-70% in agricultural systems has been exacerbated by agricultural intensification (Don *et al*., 2015). Low SOC content has a negative effect on soil health especially in Sub-Saharan Africa, resulting in lower productivity and increased poverty (Nkonya *et al*., 2015). This is due to low biomass production, reduced soil organic matter input, intensive cultivation and low crop residue addition, which can be associated with socioeconomic and biophysical factors (Saiz *et al*., 2012; Allen *et al*., 2011). In Kenya, smallholder-farming systems with low SOC are characterized by a low soil productivity (Moebius-Clune *et al*., 2011). Sommer (2017), reported SOC losses of 50 -70% in western Kenya due to unsustainable practices such as continuous tillage, intensified crop production without or with minimal replenishment of depleted soil nutrients. In addition, land use change from forests to cultivation systems, continuous mono-cropping and low inputs was reported to be responsible for decline in soil fertility (Campos, 2020, Moebius-Clune *et al*., 2011). In Western Kenya, Waswa (2012) reported low SOC levels in most smallholder farms. The SOC concentration was way below the threshold value of 2%, making the systems more susceptible to soil degradation. However, conservation tillage, crop rotation, agroforestry, and intercropping, among other agricultural management techniques, may help to restore lost carbon and degraded land, resulting in improved soil health and quality (Manna *et al*., 2015; Lal, 2010).

While much research has been done on how judicial agricultural management practices affect SOC, there is a scarcity of information on short- to medium-term monitoring of the effects of site-specific practices and determining the best management strategy (Jackson *et al.*, 2017, Don *et al.*, 2015). Model simulation to predict future trends of SOC levels under varied management practices is touted as the best approach towards monitoring the effect of site-specific activities on SOC. CropSyst is one such simulation model that can be used for this purpose (Stöckle *et al*., 2003). CropSyst is a biophysical, mechanistic, daily time step model and serves as analytical tool to study the effect of cropping systems management on crop productivity and the environment. It can be used to simulate crop yield, residue production and decomposition, soil-water budget and soil erosion by water (Stöckle *et al*., 2003). It is capable of simulating SOC levels under different management practices and their potential for sequestration (Sommer, 2017). In this study, it will be used to simulate SOC dynamics under business-as-usual and best-bet agricultural management practices in the short to medium term future. The overall objective of the study was to determine the impact of smallholder farmers' management practices on SOC levels and potential for sequestration in western Kenya.

1.2 Statement of the Problem

Declining SOC within smallholder farming system is a contributory factor to reduced soil fertility (Gomiero, 2016; Lal 2006; Cheesman *et al*., 2016). The contribution of smallholder farmers' agricultural practices on SOC dynamics and how their management practices contribute to soil health and productivity or otherwise are not well documented (Droppelmann *et al*., 2017; Moebius-Clune *et al*., 2011). Most research investigating the management practices effect on SOC content often fails to consider short, medium and long-term variations in biophysical environment (Jackson *et al*., 2017). Agricultural practices that restore, retain or increase SOC and how the same can be harnessed to increase soil fertility and productivity through long-term monitoring has thus not been explored (Swanepoel *et al*., 2018; Jackson *et al*., 2017, Don *et al*., 2015). Thus, to enhance SOC stocks in smallholder farming systems, short to long-term monitoring of different agricultural management practices on SOC stocks need to be explored.

1.3 Justification

SOC loss in most smallholder farms is the main contributing factor to declining soil fertility and productivity and, consequently food insecurity and poor resilience to climate change. Low SOC can be addressed through identification (through surveys of farmer tested and proven management practices that maintain and/or increase carbon levels). Simulation of the various agricultural management practices in the context of carbon sequestration will confirm their effectiveness and sustainability in the long-term effects. The surveys and simulation of farmer management practices will single out best management practices for recommendation and subsequent adoption by farmers. Consequently, soil fertility and agricultural yields will be enhanced ultimately leading to food sufficiency, and improved livelihoods. This will also increase adaptation to climate change and other shocks through the enhanced carbon sequestration. In addition, soil ecosystem services and ecological functions will be enhanced. The best management practices established could also be used to inform development of a policy framework to guide climate resilient and sustainable agricultural management practices in smallholder farms of western Kenya.

1.4 Objectives

1.4.1. Broad objective

To assess the impact of smallholder farmers' management practices on SOC stocks and associated soil physicochemical properties in western Kenya.

1.4.2. Specific Objectives

1. To evaluate agricultural management practices among smallholder farmers of western Kenya and their influence on SOC stocks;
2. To assess the effect of SOC stocks on soil physiochemical properties in smallholder farms of Western Kenya;
3. To simulate SOC dynamics under business-as-usual and improved management scenarios.

1.5 Hypothesis

1. Smallholder farmers in western Kenya operate under varied biophysical environments and apply different agricultural management practices on their farms which influences SOC
2. Soil chemical or physical properties influences SOC in smallholder farms of western Kenya
3. Model-based projections reveal that under business-as-usual management, soils in Western Kenya are losing carbon while under conservation agriculture, soils potentially sequester carbon

CHAPTER TWO: LITERATURE REVIEW

2.1 Smallholder farming systems and associated management practices

Smallholder farmers are small-scale farmers having land sizes ranging from one to ten hectares globally (FAO, 2015). In Sub-Saharan Africa, smallholder farmers manage eighty percent of the farms (FAO, 2015; Waswa, 2012) mainly cultivating Maize *(Zea mays*) frequently intercropped with beans (*Phaseolus vulgaris*). The crops are cultivated annually mainly for subsistence, with hand hoe and animal traction as a tillage operation (Odhiambo *et al*., 2015) but with limited inputs (Blecourt *et al*., 2019). Limited inputs result in a loss of soil quality and productivity affecting their livelihoods negatively (Bryan *et al*., 2011) as it provides income to 1.3 billion smallholder farmers (Kweyu, 2017). In Kenya, smallholder farmers contribute 63% of the food to the country by generating approximately 2,527 dollars of income (FAO, 2015). Smallholder farming systems in western Kenya is characterized by high population density (Valbuena *et al*., 2015) with variability in biophysical and socioeconomic environment, thus adoption of different agricultural management practices (Tittonell *et al*., 2008). These management include application of mineral fertilizers, manure and crop residue however, the application is below the recommended rates (Njoroge *et al*., 2019; Waswa, 2012). This results to decline in soil fertility and consequently negative impact on crop yields and livelihoods (Sommer, 2018; Vanlauwe *et al*., 2015).

2.2 Soil organic carbon and, Ecosystem Services and Functions

Soil organic carbon (SOC) is the main component of soil organic matter and plays critical role in provision of ecological and ecosystem functions (Bationo *et al*., 2018; Bationo *et al*., 2006; Lal, 2006). SOC improves structure of soil, cation exchange capacity, and available water capacity, thus influencing soil's physical, biological, and chemical characteristics and, consequently, soil fertility and crop productivity (Allen *et al*., 2010; FAO, 2004; Darwish and Fadel, 2017). Low SOC can be increased through carbon sequestration (Winowiecki *et al.,* 2014). Carbon sequestration is where carbon is captured from the atmosphere and stored in the soil. It is crucial strategy in mitigating the effects of climate change, improving soil fertility, and controlling soil erosion (FAO, 2017). SOC sequestration is possible by uptake of judicial agricultural management activities, such as conservation agriculture (Singh *et al*., 2018; Sombrero and Benito, 2010).

However, soil texture plays a critical factor in sequestering and maintaining SOC (Arunrat *et al.*,2020).

2.3 Agronomic management practices and their effect on SOC

Agronomic management practices are a set of operations including tillage, fertilizer application, manure use, surface residue that are adopted to increase potential crop yield and returns (Singh *et al.*, 2014).

Agronomic management practices adopted by smallholder farmers influence SOC levels and is further governed by the management history of the land, initial carbon content, level of soil fertility, period of cultivation and stability of soil organic carbon pools (Stahl *et al.*, 2016; Song *et al.*, 2013; Batjes, 2010; Kimetu *et al.*, 2008; Thomson *et al.*, 2006). The management practices include application of mineral fertilizer, manure, crop residue retention and soil and water conservation practices (Waswa *et al.*, 2013; Nandwa, 2001).

Application of chemical fertilizer is one of the predominant management practices in smallholder farming systems (Waswa and Kihara, 2014) leading to high heterogeneity in soil fertility (Mugwe *et al.*, 2009). Fertilizer use is determined by productivity of the soil (Marenya *et al.*, 2009),value of crops (Omamo *et al.*, 2002), ownership of the land, cost, resources available and gender (Ariga and Jayne, 2011). Although farmers use fertilizer, they apply rates way below the recommended amount of 60 kg N ha^{-1} and 30 kg P ha^{-1} (KALRO-KCEP, 2016; FAO and ITPS, 2015). Inadequate use of fertilizer is attributed to unaffordability (Lemenih *et al.*, 2005), low response of fertilizer to crop yields due low SOC levels (Salat and Swallow, 2018) and high poverty levels (Ehui and Pender 2005). SOC content influences fertilizer uptake and utilization (Ichami *et al.*, 2019; Ngetich *et al.*, 2009) thus crucial to improve carbon concentration and consequently availability of nutrients. Chemical fertilizer application was reported to have an important effect on SOC (Salat and Swallow, 2018) with either a positive or negative response.

According to Njoroge *et al*. (2019), frequent application of fertilizers reduced the availability of nutrients with no notable changes in SOC content due to slow decomposition of organic matter. Fertilizer alone did not increase or maintain SOC content (Liu *et al.*, 2016; Su *et al.*, 2006; Wang *et al.*, 2006). Lal (2004) reported fertilizer application increased yields with no significant influence on SOC unless coupled with crop residue retention. A decrease in SOC content was attributed to reduced microbial activity (Kumar *et al*., 2016; Zhong *et al*., 2015; Li *et al*., 2013), phosphorus-based fertilizers (Li et al., 2018), reduced root surface area (Kane, 2015).

However, contradictory results were reported where fertilizer addition was reported to increase SOC content (Jiang *et al*., 2018; Liang *et al*., 2016; Zhong *et al*., 2015; Song *et al*., 2013; Poeplau *et al*., 2017; Bationo *et al*., 2006) with a substantial increase in the plough layer (Zhang *et al*., 2015).

Animal manure is also another management practice among smallholder systems (Musinguzi *et al*., 2013) because it is affordable and readily available (Place *et al*., 2003). Also, most farmers remove almost all the residue for livestock feed, thus manure being the alternative input (Castellanos-Navarrete *et al*., 2015). Manure ameliorate the chemical and biological and physical characteristics (Dhillon *et al*., 2018; Ngetich *et al*., 2009), particularly structure of the soil, drainage and water-absorption capacity (Jiang *et al*., 2018) thus restoring the fertility (Mangalassery *et al*., 2019; Waswa *et al*., 2007; Place *et al*., 2003). In western Kenya, farmers apply approximately 2.5 t ha^{-1} thus inadequate as the recommended amount is 7 t ha^{-1} (Castellanos-Navarrete *et al*., 2015; Ehui and Pender 2005) with an average application of 0.9 to 4 t ha/yr (Tittonell *et al*., 2008). This is attributed to ownership of livestock, land size, and labor availability with the manure's quality affected by grazing and storage systems (Waithaka *et al*., 2007). Hence, unable to restock the deficient nutrients(Han *et al*., 2016), increase SOC and crop yields (Tittonell *et al*., 2008). Further, manure applied are of low quality though the efficiency can be improved by application in splits (Tittonell *et al*., 2010). Management strategies, quantity applied, properties of the soil, initial carbon content, and climate all influence the outcome of manure application on SOC sequestration (Merante *et al*., 2017; Maillard *et al*., 2014). Manure has been shown to improve SOC levels. (Aula *et al*., 2016; Mugwe et al., 2009; Kimetu *et al*., 2008; Mucheru-Muna *et al*., 2007; Bationo *et al*., 2006) with a significant increase where manure was applied frequently over a prolonged period (Njoroge *et al*., 2019). The amount and composition of manure, as well as the application period, affected the role of manure on SOC content, resulting in different SOC pool concentrations (Waswa *et al*., 2007). Increased SOC content was more prevalent when manure with different characteristics was applied (Ren *et al*., 2014). On the contrary, Tittonell *et al*. (2010) reported no notable improvement in SOC content due to the manure's poor quality. Low SOC can be reversed by applying manure that has been stored for less period since it has high nutrients and carbon. Sommer *et al*. (2018) found out that manure application did not increase SOC level was attributed to the method of manure application, past land use and soil mineralogy.

Crop residue is also another organic input and source of nutrients (Musinguzi *et al*., 2013). Adoption of crop residue retention as a management practice is very low among smallholder farmers <0.5 t/ha due to competing needs such as fuel, livestock feed, building material (Salat and Swallow, 2018; Mujuru *et al*., 2016; Bationo *et al*., 2006). Crop residue retention on the surface has multiple benefits on the soil by improving the chemical, physical and biological characteristics. It improves overall soil health by reducing soil erosion, efficient nutrient uptake, and increased water holding capacity, aggregate stability and improved carbon levels through addition of organic matter. Benefits resulting from retention of crop residue retention are site specific relying on the agricultural management activities, amount of crop residue and quality, soil type and socio-economic conditions. In humid areas such as western Kenya surface application of crop residue is recommended than incorporation since it will slow down the decomposition rate thus increase the SOC content especially at the plow layer (Droppelmann *et al*., 2017; Merante *et al*., 2017; Turmel *et al*., 2014; Guto *et al*., 2012).

In western Kenya, SOC concentration was increased when crop residue coupled with reduced-tillage was implemented (Guto *et al*., 2012; Sanderman and Baldock, 2010) with a significant effect more pronounced on the upper layer (Sommer *et al*., 2018) and in the labile fraction (Kimetu *et al*., 2008). On the contrary, SOC was reported to increase in deeper layers due to lower mineralization rate compared to surface application thus critical for carbon sequestration over an extensive period (Poeplau *et al*., 2017; Blanco-Canqui and Lal, 2008; Pandiaraj *et al*., 2000). However, some studies reported no increase in SOC content or improvement in soil structure when crop residue was applied and it was attributed to low quantity and high decomposition rate of crop residues (Njoroge *et al*., 2019; Munthali *et al*., 2015; Paul *et al*., 2013; Ayuke *et al*., 2011; Ngetich *et al*., 2009) and termite attack (Okeyo *et al*., 2016). Different proportion of crop residue influences SOC concentration and crop productivity thus essential to identify site-specific management of crop residues (Raffa *et al*., 2015).

The adopted agronomic management practices by smallholder farmers result to variability of SOC levels (Vanlauwe *et al*., 2014). This variability within smallholder farms is determined mainly by management practices and access to resources (Masvaya *et al.*, 2010). The variability makes it essential to identify site-specific management of crop residues, manure and chemical fertilizer use particularly at lower depth (Raffa *et al*., 2015; Ren *et al*., 2014). Further, it is critical to monitor the effect of these management practices over a long duration (Njoroge *et al*., 2019; Poeplau *et al*., 2017). In addition to identifying site-specific management practices, soil physicochemical practices need to be considered since they strongly interact leading to wide variability in SOC levels.

2.4 Soil physicochemical properties and their effect on SOC

Physical factors include bulk density, soil texture and aggregate stability. Bulk density strongly correlates with SOC and is mainly influenced by soil texture (Nyberg *et al*., 2012). An increase in bulk density lowers carbon concentration in soils while lower bulk density increases SOC content (Chaudhari *et al*., 2013). Smallholder systems have low SOC as a consequent of increased bulk density (Nwaogu *et al*., 2018). This is contributed by increased compaction due to conventional tillage, erosion, and aggregate instability (Paul *et al*., 2015; Nyberg *et al*., 2012). Soil texture influences soil organic matter decomposition thus affecting SOC levels and carbon sequestration potential (Singh *et al*., 2018; Kimetu *et al*., 2008). Clay and silt soils have been reported to have high SOC content because they protect SOC from decomposition and has a high association of organic matter on mineral surfaces (Poeplau *et al*., 2017; Mujuru *et al*., 2016). Sandy soils have less SOC with reports as low as 1% (Musinguzi *et al*., 2013; Albrecht *et al*., 2005) low organic matter association on mineral surfaces, low nutrient content, poor aggregate stability, and reduced water-holding capacity (Nyberg *et al*., 2012; Saiz *et al*., 2012).

Chemical properties that influence SOC content include phosphorus, carbon to nitrogen ratio, nitrogen, cation exchange capacity, exchangeable aluminum, pH, and micronutrients. Phosphorus is a crucial nutrient required for growth of roots and elongation (Ratnayake *et al*., 2014; Ahmed *et al*., 2005). However, it is deficient among smallholder farmers due to microbial fixation, high aluminum content, unbalanced mineral fertilizer application, and a long period of cultivation (Musinguzi *et al*., 2016; Moebius-Clune *et al*., 2011). Phosphorus content affects SOC stocks with high phosphorus concentration resulting in increased SOC stocks through increased biomass production (Njoroge *et al*., 2019). Carbon to nitrogen ratio is important in governing decomposition and ultimately SOC stocks with high C/N lowering decomposition rate and vice versa (Gebeyehu and Soromessa, 2018; Musinguzi *et al*., 2013). SOC and nitrogen are highly associated (Gebeyehu and Soromessa, 2018). Nitrogen content influences soil organic matter decomposition, which in turn promotes the different organic matter fractions (Waswa *et al*., 2007). Cation exchange capacity affects nutrient availability (Schweizer *et al*., 2018). Low cation exchange capacity lowers the SOC because of reduced capacity of the soil to store carbon (Pal and Marschner, 2016). High levels of exchangeable aluminum in the soils increases SOC content by stabilizing SOC through binding of organic matter (Tsozué *et al*., 2019).

Soil pH is also an important parameter that affects the soil fertility by determining the solubility and availability of nutrients (Kabirinejad *et al*., 2014). Soil pH influences the SOC stocks and increases its concentration especially at near-neutral pH because of increased microbial activity (Benbi and Brar, 2009). Micronutrients are important in the soil since they improve soil and crop productivity though they are required in small quantities compared to macronutrients. Most soils in western Kenya have micronutrient deficiency particularly copper and zinc (Njoroge *et al*., 2017). Micronutrient concentration is mainly impacted by pH (Kabirinejad *et al*., 2014; Rutkowska *et al*., 2014). Zinc, manganese, iron and copper are essential micronutrients since they influence crop productivity thus influencing biomass productivity and consequently organic matter in terms of quantity of crop residue retained (Kabirinejad *et al*., 2014; Rutkowska *et al*., 2014; Shah & Andrabi, 2009). Hence proving critical to assess the influence of the physicochemical properties on SOC.

In addition to measuring SOC levels in the fields, crop modelling has proven to be an effective and flexible way to project the impact of agricultural management practices, which can contribute to mitigating climate change (Gupta and Kumar, 2017). Further models can predict short to long-term SOC dynamics and sequestration potential under varied management practices (Hashimoto *et al*., 2012; Wan *et al*., 2011) thus easier to identify practices that improve SOC content.

2.5 Agroecosystem models

Agroecosystem models are tools that integrate environmental conditions and management factors to predict crop growth and development and change in climate in the future (Asseng *et al*., 2013; Li *et al*., 2012). Agroecosystems models evaluate and predict the influence of interaction among management, climate and soil on SOC stocks, greenhouse gas emission, nitrogen leaching and crop productivity (Jones *et al*., 2016). Several studies have used models to predict SOC dynamics and include CENTURY (Parton *et al*., 1987; Kwon *et al*., 2017), RothC (Coleman and Jenkinson

1996), DAYCENT (Del Grosso *et al*., 2012; Chang *et al*., 2013), DAISY (Mueller *et al*., 1996), CANDY (Franko, 1996), CQESTR (Gollany *et al*., 2018), SOCRATES (Grace *et al*., 2000), and CropSyst (Stöckle *et al*., 2003). In this study, we are going to use CropSyst model because of minimal data input. Further, compared to other models, CropSyst has been extensively calibrated and successfully used in our study area. CropSyst is a multi-year, multi-crop, daily time-step cropping systems simulation model developed to serve as an analytical tool to study the effect of climate, soils and management on cropping systems productivity and the environment. It simulates crop growth and development, residue production and decomposition, soil water budgets and erosion. Management options include; cultivar selection, crop rotation, irrigation, nitrogen fertilization, residue management and tillage operations (Stöckle *et al*., 2003). CropSyst has been applied in western Kenya to simulate potential carbon sequestration under a set of soil fertility improvement practices and conservation agriculture (Sommer *et al*., 2018; Sommer, 2017), in Italy (Rinaldi *et al*., 2017), West Africa (Badini *et al*., 2007), Mexico (Sommer *et al*., 2007), USA (Stöckle *et al*., 2010). Compared to other models, CropSyst can simulate SOC in point-scale, regional and global scale (Nyawira 2019). Further the model has been successful in simulating SOC under different climate, soil and crop conditions (Sommer *et al*., 2016; Sommer *et al*., 2007). In this study it will be used to simulate SOC dynamics under business-as-usual as opposed to conservation management practices.

CHAPTER THREE: INFLUENCE OF AGRICULTURAL MANAGEMENT PRACTICES ON SOIL ORGANIC CARBON IN SMALLHOLDER FARMS OF WESTERN KENYA

3.1 Abstract

Declining soil organic carbon (SOC) content among smallholder farmers is majorly attributed to the different agricultural management practices. A plethora of literature is available on research that has been done on effect of agricultural management practices on SOC however, there is paucity of information on site-specific management that improve and sustain SOC content. The specific aim of the study was to evaluate the predominant agronomic management activities and their influence on SOC down the depth. Using secondary data on household surveys from an earlier on-farm survey, a list of farms was generated. Farms with odd numbers and those that have been practicing cultivation for more than 10 years were chosen at random. A total of 60 farms were selected, with 30 farmers selected from Shikomoli (Vihiga) and 30 farms from Mukuyu (Kakamega) villages. Data on land use history, inputs, crop residue retention and soil and water conservation measures were collected. In addition, soil samples were obtained at three depths 0-20 cm, 20-40 cm and 40-60 cm and analysed SOC content. In both sites the predominant management practice was manure in combination with chemical fertilizer. Trenches and grass strips were the main soil and water conservation practices applied in both sites with 27% users in Shikomoli and 64% users in Mukuyu. The SOC stock (Mg/ha) content analysis results showed significantly higher SOC stocks in Mukuyu (40.4 Mg/ha) and Shikomoli (29 Mg/ha) under combined application of manure, fertilizer and crop residues. The lowest SOC stock resulted from combined application of fertilizer and crop residue in Mukuyu (of 32 Mg/ha) and manure combined with chemical fertilizer in Shikomoli (22.2 Mg/ha). SOC stocks reduced down the depth in Shikomoli at 0-20 cm depth (26.91 Mg/ha), 20-40 cm (24.17 Mg/ha) and 40-60 cm depth (22.56 Mg/ha) while in Mukuyu at 0-20 cm (40.01 Mg/ha), 20-40 cm (33.83 Mg/ha) and 40-60 cm (30.11 Mg/ha). To enhance SOC stocks among smallholder farmers in both sites best management practices include combination of crop residue, mineral fertilizer and manure.

Key words: soil organic carbon, Agricultural management practices, smallholder farms, soil health: Kenya

3.2 Introduction

Soils are the largest terrestrial organic pool and mainly governed by the interaction between climate, type of soil and agronomic management practices (Yigini and Panagos, 2016; Pan *et al*., 2013). Soil organic carbon (SOC) governs nutrient availability, provision of essential ecosystem services, improving soil physicochemical properties, sustaining fertility of the soil and thus the critical measure of soil health and crop productivity. However, smallholder-farming systems have reported low SOC levels (FAO and ITPS, 2015). The low levels are prevalent especially in Western Kenya due to different agricultural management practices and inherently low soil fertility (Njoroge *et al*., 2019; Tittonell *et al*., 2008) thus, loss of soil quality and productivity of crops (Moebius-clune *et al*., 2011) with yields hardly surpassing 0.5 t/ha (Bationo *et al*., 2014). Waswa (2012), working in Western Kenya, reported low SOC content in most smallholder farms that were way below the threshold value of 2%, making the systems more susceptible to soil degradation. A study by Sommer (2017), in western Kenya reported SOC losses of 50 -70% due to unsuitable practices such as continuous tillage and continuous tillage with limited inputs.

Therefore, implementation of site-specific judicial management activities including conservation tillage, crop rotation, agroforestry and intercropping is crucial to improve SOC concentrations, soil fertility and crop productivity (Mangalassery *et al*., 2019; Zomer *et al*., 2017; Musinguzi *et al*., 2016; Manna *et al*., 2015; Batjes, 2010; Lal, 2010).

Agricultural management practices put into place by farmers to improve the inherently low soil fertility are mainly determined by the farmers essential needs, socio-economic conditions, land size, labour availability, biophysical conditions and willingness to alter existing farming systems (Duval *et al*., 2018; Mujuru *et al*., 2016 Ojiem *et al*., 2006; Okeyo *et al*., 2006). Unfortunately, the inputs added to the soil are limited due to competing needs (Waswa and Kihara, 2014) and unavailability of resources (Zomer *et al*., 2017; Moebius-Clune *et al*., 2011). Agronomic management practices adopted by smallholder farmers to improve soil fertility include application of mineral fertilizer, manure, crop residue, and soil and water conservation practices (Waswa *et al*., 2013; Nandwa, 2001). However, the effect of these practices on SOC is affected by management history of the land, initial carbon content, level of soil fertility, period of cultivation and stability of SOC pools (Stahl *et al*., 2016; Song *et al*., 2013; Batjes, 2010; Kimetu *et al*., 2008).

In addition, a plethora of literature exists on the impact of the management activities on SOC levels however, there is limited information on the site-specific management practices that improve and/or sustain carbon content down the depth (Cook and Trlica, 2016; Lal, 2016). Therefore, this study was conducted to determine the impact of common smallholder-farming management practices on SOC levels at different depths in the Vihiga and Kakamega sub-counties of western Kenya.

3.3 Materials and Methods

3.3.1 Description of study site

The study was carried out using secondary data from two sites in Western Kenya: Mukuyu village in Lugari Sub-County, Kakamega County and Shikomoli village in Hamisi Sub-County Vihiga County (Fig. 3.1). The two villages were selected due to low SOC levels and yields.

Shikomoli is located between latitude and longitude of 0^0 03' 09" N to 0^0 03' 78" N and 34^0 46' 80" E to 34^0 47' 25" E at an altitude of 1400 meters above sea level. The annual rainfall ranged from 1600 to 2000 mm and a mean rainfall of approximately 1700 mm, characterized by a long rain season (February-July) and a short rain season (August-December). The daily temperatures range between 14 °C and 32 °C with a mean of 23 °C. The main type of soils are Cambisols (Jaetzold *et al.*, 2010). Maize (*Zea mays*) is the major crop grown, and it is often intercropped with common beans (*Phaseolus vulgaris*) (Diwani *et al.*, 2013). Due to intensive cultivation with little or no nutrient or organic matter inputs, the area has been identified as having declining soil quality and productivity. (Tittonell *et al.*, 2007).

Mukuyu is located between latitude and longitude of 0^0 43' 96" N to 0^0 44' 15" N and 34^0 55' 96" E to 34^0 56' 37" E at an altitude of 1600 meters above sea level. The annual rainfall is somewhat lower than that of Shikomoli ranging between 1000 to 1600 mm (average ~1450 mm) but characterized by the same bimodal annual rainfall regime. The daily temperatures ranged from 14 °C to 26 °C and a mean of 20 °C – i.e., a little colder than Shikomoli given its slightly higher altitude. Ferralsols are the main soil type (Jaetzold *et al.*, 2009) in Mukuyu. As in Shikomoli, maize is the major crop grown, sometimes intercropped with beans (Waithaka *et al.*, 2007).

The dominant management practices in both sites include the use of inorganic fertilizer mainly diammonium phosphate (DAP) supplied at an average rate of 135 kg/ha in Mukuyu and 72 kg/ha in Shikomoli and farmyard manure/compost (Munialo *et al.*, 2019; Jaetzold *et al.*, 2009).

Figure 1. Counties of study sites in Western Kenya (Source: Author)

3.3.2 Study Approach

Farmer Selection: Using secondary data on household surveys from an earlier on-farm survey (AFRINT III 2013), a list of farms was generated. Farms with odd numbers and those that had been practicing cultivation for more than 10 years were chosen at random. A total of 60 farms, 30 farms in Shikomoli village in Vihiga and 30 farms in Mukuyu village in Kakamega were selected. The sample size of farms represented different biophysical environment including soil type, climate and management practices.

3.3.2.1 Assessing the predominant agronomic management practices

A survey was conducted in two villages (Shikomoli and Mukuyu) in western Kenya to determine the major agricultural management activities and their influence on soil organic carbon. A semi-structured questionnaire was administered through interviews to the randomly 60 selected farmers, 30 in Mukuyu village in Kakamega and 30 in Shikomoli village in Vihiga. The key elements in the questionnaire were land-use history, inputs, management of crop residue and soil and water conservation measures.

3.3.2.2 Soil Sampling and analysis

Soil samples were obtained from the selected categories of farms within a quadrat. A plot which has been under maize cultivation for more than 10 years was identified per farmer making a total of 60 plots. The size of the quadrat depended on the size of the plot per farmer. Within each quadrat of every plot, five spots were randomly selected, and samples collected at three subsequent depth 0-20 cm, 20-40 cm and 40-60 cm. Composite samples of about 500 g were collected at each depth in each plot. 3 samples were taken from each plot, totalling 180 samples for the 60 farms. The bulk density of the soil was determined by collecting samples with a cylindrical core ring at each subsequent depth from the middle of the plot. Geographical position and elevation were also recorded using geographical position system (GPS) device. Soil samples collected were then taken to the laboratory for analysis.

Physical Soil Analysis: Bulk density was determined by oven drying at 105 ^{0}C for 48 hours to a constant weight (Blake, 1965). Bulk density (g/cm^3) was determined as a ratio between dry weight of the soil and volume of soil core.

Chemical Soil Analysis: Air-dried soil samples were grounded and 2mm sieved and then weighed. The total carbon and total nitrogen were measured by oxidation using a C/N elemental analyser (Macro Cube, Elementar GmbH, Germany). The elemental analyser through combustion releases gases containing carbon and nitrogen which are further oxidized to release carbon (iv) oxide and nitrogen gas which their concentration was equated to total SOC and organic nitrogen (Sommer *et al*., 2018).

Estimation of Soil Organic Carbon Stocks: Soil organic carbon stocks was determined by multiplying measured total SOC, bulk density equation and the individual depth (Poeplau and Don, 2015).

3.3.7 Data Analysis

Survey data obtained from the questionnaire was analyzed for descriptive statistics and Pearson correlation using Statistical Packages for Social Sciences (SPSS version 23). Soil data was subjected to analysis of variance (ANOVA) using R software (version 3.4.1). All statistical significance was determined at $P < 0.05$.

3.4 Results

3.4.1 Sociodemographic and biophysical characteristics

About 70% of the respondent farmers were female and 30% were male out of the 30 selected farmers in Shikomoli village, while in Mukuyu, 53% of the respondents were female and 47% were male out of the 30 selected farmers (Table 3.1). In both villages, the higher number of respondents of farmers were females. Nearly 70% of the respondents had basic education while 30% had no basic education in Shikomoli (Table 3.1). In Mukuyu, 93% of the farmers had basic education and 7% had tertiary education with no respondents having none basic education. The average age of farmers were 57 (Shikomoli and Mukuyu) years with the oldest being 79 (Shikomoli) and 88 (Mukuyu) and youngest 30 across sites (Table 3.1). The average land size was 0.17 and 0.63 ha and ranged between 0.11 and 0.10 ha and 0.91 and 2.02 in Shikomoli and 0.63 Mukuyu, respectively. In both sites, the majority of farms had a flat slope with 63% of the farm slope being flat, 33% gently sloping and 3% steep in Shikomoli (Table 3.1). In Mukuyu, 63% of the farm was flat, 33% was gently sloping and 3% was steep (Table 3.1). In Shikomoli, 23% had no erosion, 63% had slight erosion and 13% had severe erosion (Table 3.1).

In Mukuyu, 13 % had no erosion, 63% had slight erosion and 23% had severe erosion. In Shikomoli, 93% of the respondents had livestock while 7% had no livestock (Table 3.1). In Mukuyu, 90% of farmers had livestock and 10% no livestock.

Table 1. Socio-demographic and biophysical characteristics of selected farmers in Mukuyu and Shikomoli with the proportions in percentage

Parameter		**No. of farmers with frequency (n=60) % of the variables**	
		Shikomoli (n = 30) % of the variables	**Mukuyu (n=30) % of the variables**
Gender			
	Female	70	53
	Male	30	47
Level of education			
	None	30	
	Primary	47	93
	Tertiary	23	7
Slope			
	Flat	63	63
	Gently sloping	33	33
	Steep	3	3
Erosion			
	None	23	13
	Slight	63	63
	Severe	13	23
Livestock ownership			
	Yes	93	90
	No	7	10
Age			
	Average	57	57
	Minimum	30	30
	Maximum	79	88
Land size (ha)			
	Average	0.17	0.63
	Minimum	0.11	0.10
	Maximum	0.91	2.02

n represents the sample size of farmers

3.4.2 Agricultural management practices

Management practices taken up by farmers included use of chemical fertilizer alone (F), chemical fertilizer + manure (FM), chemical fertilizer + crop residue retention (FC) and chemical fertilizer + manure + crop residue retention (FMC).

Users of manure in combination with chemical fertilizer were 57% in Shikomoli and 40% in Mukuyu, users of manure combined with crop residue retention and chemical fertilizer were 26% in Shikomoli and 10% in Mukuyu, users of chemical fertilizer alone were 17% in Shikomoli and 33% in Mukuyu and users of chemical fertilizer in combination with crop residue retention were 17% in Mukuyu alone (Figure 3.2).

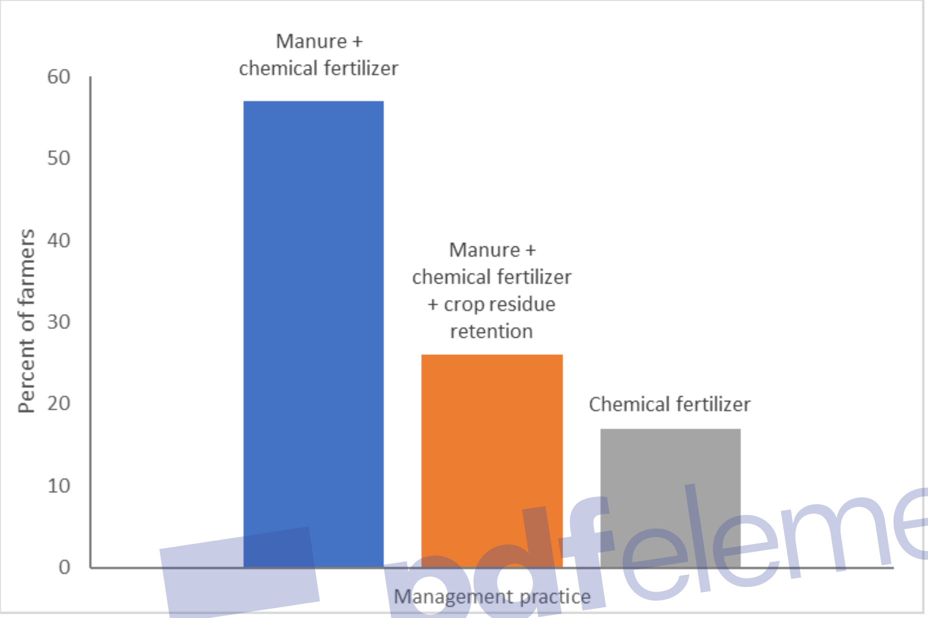

Figure 2. Predominant agronomic practices in Shikomoli

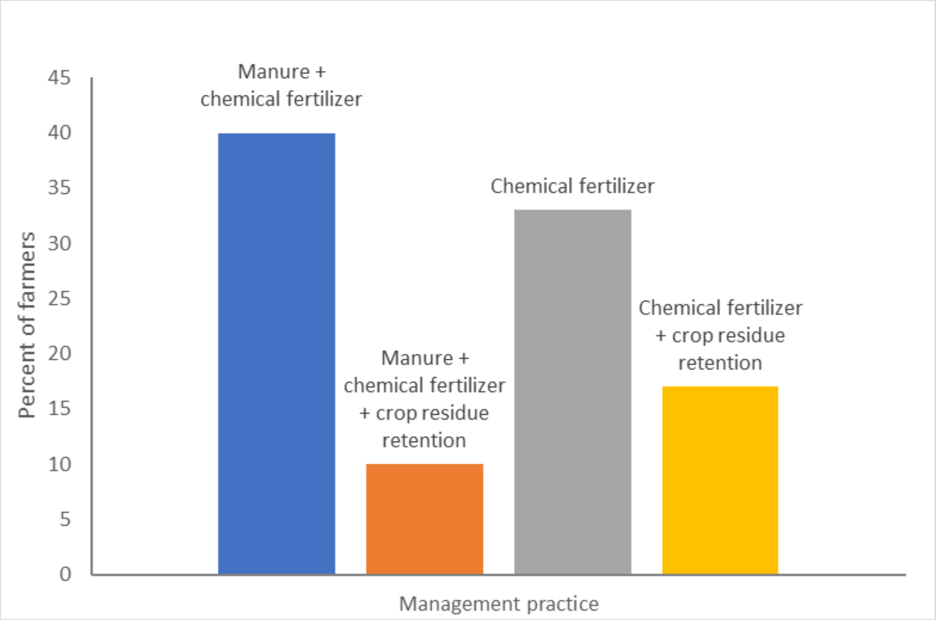

Figure 3. Predominant agronomic practices in Mukuyu

3.4.3 Land use history and management for the past three years before the year of study

In the past three years in Shikomoli, all the farmers (100%) cultivated using hand hoe as the main tillage practice while 30% of the farms in Mukuyu used tractor and animal traction, users of manure were 87% in Shikomoli and 67% in Mukuyu, users of maize-bean intercrop were 80% in Shikomoli and 53% in Mukuyu, users of chemical fertilizer were 97% in Shikomoli and 100% in Mukuyu, users of agroforestry were 21% in Shikomoli and 7% in Mukuyu and users if crop residue were 53% in Shikomoli and 60% in Mukuyu (Table 3.2).

Table 1. Land use and management for the past three years before the year of study

	2015		**2016**		**2017**	
	Frequency in percentage (n=60)					
Management	**Shikomoli**	**Mukuyu**	**Shikomoli**	**Mukuyu**	**Shikomoli**	**Mukuyu**
Tillage with hand hoe	100	0	100	0	100	0
Tillage with animal traction	0	27	0	27	0	27
Tillage with tractor	0	27	0	27	0	27
Tillage with tractor in combination with animal traction	0	30	0	30	0	30
Tillage with animal in combination with hand hoe	0	3	0	7	0	7
Tillage with tractor in combination hand hoe	0	7	0	7	0	7
Tillage with hand hoe	0	7	0	7	0	7
Application of manure	87	67	87	67	87	67
Crop type planted including maize and beans	80	53	80	53	80	53
Application of chemical fertilizer	97	100	97	100	97	100
Practice of agroforestry	21	7	21	7	21	7
No practice of agroforestry	79	93	79	93	79	93
Crop residue retention (retaining crop residue after harvest)	53	60	53	60	53	60

n represents sample size

3.4.4 Inputs applied and soil and water conservation measures

Users of inorganic fertilizer were 97% in Shikomoli and 100%, the main method of application for fertilizers was incorporation during planting and topdressing after crop emergence in both sites with 35% in Shikomoli and 77% in Mukuyu (Table 3.3). In both sites, the source of inorganic fertilizer was agrovet shops with 63% in Shikomoli and 53% in Mukuyu with other sources such from One Acre Fund (non-profit organization), children and relatives of the family purchased the inorganic fertilizer and received from the county government (Table 3.3). Users of organic fertilizer were 87% in Shikomoli and 47% in Mukuyu, users of compost manure were 46% in Shikomoli and 97% in Mukuyu, users of livestock manure were 37% in Shikomoli and 3% in Mukuyu and users of chicken manure were 17% in Shikomoli alone with application mostly done during land preparation, the organic fertilizer was source from on-farm production (Table 3.3). In addition, users of soil and water conservation practices including trenches and grass strips were 60% in Shikomoli and 80% in Mukuyu (Table 3.3).

Table 3. Agricultural management practices for the year of study including the inputs applied, types of inputs, source of inputs, time of application of inputs, tillage operations and soil and water conservation practices

Parameters	**No. of farmers frequency (n=60) % of the variables**	
	Shikomoli (n=30)	**Mukuyu (n=30)**
Inorganic fertilizer		
Application inorganic fertilizer	97	100
No application of inorganic fertilizer	3	0
Type of fertilizer		
DAP + CAN	35	57
Method of application		
Incorporate + top-dressed	35	77
Source of inorganic fertilizer		
Agrovet	63	53
Organic fertilizer use		
Use of organic fertilizer	87	47
No use of organic fertilizer	13	53
Type of organic fertilizer used		
Compost manure	46	97
Livestock manure	37	3
Chicken manure	17	?
Time of fertilizer application		
Land preparation	19	93
Planting	46	7
Land preparation + Planting	31	?
Land preparation and when crop has emerged	4	?
Source of organic		
On farm production	100	100
Proportion of residue retained		
	60	43
Tillage method used		
Hand hoe	97	13
Tractor	3	40
Animal traction	0	37
Tractor + animal traction	0	10
Soil and water conservation measures		
None	40	20
Trenches	7	30
Grass strips	33	16
Trenches + grass strips	20	34

n represents the sample size; DAP-Diammonium phosphate; CAN-Calcium ammonium nitrate

3.4.5 Correlation of management practices with SOC stocks in Shikomoli and Mukuyu

Shikomoli

Based on Pearson correlation 0.38 ($p < 0.05$), proportion of crop residues retained and SOC indicated positive linear correlation at 0-20 cm and 20-40 cm (Table 3.4). A negative linear correlation between land size and SOC at 0-20 cm depth was observed, Pearson correlation= -0.37 ($p < 0.05$) (two-sided, two-tailed).

Also, slope of land and SOC indicated positive linear correlation at 0-20 cm, Pearson correlation 0.44 ($p < 0.05$) (two-sided, two-tailed. A positive linear correlation was observed between slope of the land and SOC at 40-60 cm, Pearson correlation 0.40 ($p < 0.05$) (two-sided, two-tailed).

Table 4. Correlations between SOC stocks, management practice and demographic characteristics

	SOC stocks		
Variables	**0-20 cm**	**20-40 cm**	**40-60 cm**
Crop residue retention	0.38 ($p < 0.05$)	0.38 ($p < 0.05$)	
Land size	-0.37 ($p < 0.05$)		
Slope of the land	0.44 ($p < 0.05$)		0.40 ($p < 0.05$)

Mukuyu

A negative correlation was observed between tillage method used and SOC at 0-20 cm, Pearson correlation -0.41 ($p < 0.05$) (Table 3.5). Tillage method used and SOC showed negative correlation at 20-40 cm, Pearson correlation -0.40 ($p < 0.05$) (two-sided, two-tailed). Results indicate a positive correlation between erosion control measures in place and SOC at 0-20 cm Pearson correlation 0.44 ($p < 0.05$) (two-sided, two-tailed). There was a positive correlation between erosion control measures in place and SOC at 20-40 cm, Pearson correlation 0.39 ($p < 0.05$) (two-sided, two-tailed). A positive correlation was observed between erosion control measures in place and SOC at 40-60 cm depth, Pearson correlation 0.38 ($p < 0.05$) (two-sided, two-tailed) (table 3.5).

Table 5. Correlations between SOC stocks and management practices

	SOC stocks		
Variables	**0-20 cm**	**20-40 cm**	**40-60 cm**
Tillage method	-0.41 ($p < 0.05$)	-0.40 ($p < 0.05$)	
Erosion control measures	0.44 ($p < 0.05$)	0.39 ($p < 0.05$)	0.38 ($p < 0.05$)

3.4.6 Effect of Agricultural management practices on SOC stocks, total organic carbon (TOC) and CN ratio

In Shikomoli, fertilizer combined with crop residue and manure resulted to higher SOC stocks (29.02 Mg C ha^{-1}) on the other hand combination of manure and fertilizer had the lower at 22.33 Mg C ha^{-1} (Table 3.6). In Mukuyu, manure combined with fertilizer and crop residue recorded highest SOC stocks at 40.41 Mg C ha^{-1} while the lowest SOC stocks (31.996 Mg C ha^{-1}) was observed when fertilizer and crop residue were combined (Table 3.6). In both sites, manure combined with fertilizer and crop residue resulted to high SOC stocks.

Table 6. Effect of management practices on SOC stocks. TOC (%) and CN ratio down the soil profile

Management	Depth (cm)	SOC (Mg/ha)		TOC (%)		C/N	
		Shikomoli	Mukuyu	Shikomoli	Mukuyu	Shikomoli	Mukuyu
Chemical fertilizer	0-20	27.53^{a}	39.18^{a}	0.90^{a}	1.36^{a}	10.19a	12.43^{a}
	20-40	24.32^{a}	33.65^{b}	0.76^{a}	1.12^{b}	9.66a	12.98^{a}
	40-60	22.93^{a}	30.10^{b}	0.71^{a}	1.01^{b}	9.42^{a}	13.24^{a}
	LSD	10.59	5.08	0.34	0.18	0.86	0.91
Manure + chemical fertilizer	0-20	24.03^{a}	39.57^{a}	0.78^{a}	1.44^{a}	10.62^{a}	12.50^{a}
	20-40	21.90^{a}	34.23^{ab}	0.69^{a}	1.15^{b}	10.07^{b}	12.95^{a}
	40-60	21.09^{a}	30.01^{b}	0.67^{a}	0.99^{b}	9.88^{b}	12.95^{a}
	LSD	4.01	5.55	0.13	0.26	0.53	0.81
Chemical fertilizer + manure + crop residue retention	0-20	32.66^{a}	51.12^{a}	1.12^{a}	2.01^{a}	10.95^{a}	12.77^{a}
	20-40	28.97^{ab}	35.70^{a}	0.92^{ab}	1.43^{a}	10.96^{a}	13.28^{a}
	40-60	25.44^{b}	34.40^{a}	0.80^{b}	1.26^{a}	10.42^{a}	13.31^{a}
	LSD	5.50	18.37	0.21	1.50	1.04	1.69
Chemical fertilizer + crop residue retention	0-20		36.10^{a}		1.25^{a}		12.31^{a}
	20-40		32.12^{a}		1.06^{ab}		12.85^{a}
	40-60		22.77^{b}		0.93^{b}		12.81^{a}
	$LSD_{0.05}$		7.88		0.24		1.43

SOC stocks-Soil organic carbon; TOC- Total organic carbon; C/N- Carbon Nitrogen Ratio. Means with different letters down the column are statistically different at $P < 0.05$.

Effect of chemical fertilizer on SOC stocks, TOC and CN ratio down the depth

Significant effect was observed in Mukuyu on SOC stocks down the depth with SOC stocks at 0-20 cm depth being significantly different from 20-40 cm and 40-60 cm while at 20-40 cm depth and 40-60 cm depth not being significantly different. In Mukuyu, there was a significant effect on TOC down the depth with TOC at 0-20 cm depth being significantly different from 20-40 cm and 40-60 cm depth (Table 6).

Table 6. Effect of management practices on SOC stocks. TOC and CN ratio down the soil profile

Management	Depth (cm)	SOC (Mg/ha)		TOC (%)		C/N	
		Shikomoli	Mukuyu	Shikomoli	Mukuyu	Shikomoli	Mukuyu
Chemical fertilizer	0-20	27.53^{a}	39.18^{a}	0.90^{a}	1.36^{a}	10.19a	12.43^{a}
	20-40	24.32^{a}	33.65^{b}	0.76^{a}	1.12^{b}	9.66a	12.98^{a}
	40-60	22.93^{a}	30.10^{b}	0.71^{a}	1.01^{b}	9.42^{a}	13.24^{a}
	LSD	10.59	5.08	0.34	0.18	0.86	0.91
Manure + chemical fertilizer	0-20	24.03^{a}	39.57^{a}	0.78^{a}	1.44^{a}	10.62^{a}	12.50^{a}
	20-40	21.90^{a}	34.23^{ab}	0.69^{a}	1.15^{b}	10.07^{b}	12.95^{a}
	40-60	21.09^{a}	30.01^{b}	0.67^{a}	0.99^{b}	9.88^{b}	12.95^{a}
	LSD	4.01	5.55	0.13	0.26	0.53	0.81
Chemical fertilizer +manure + crop residue retention	0-20	32.66^{a}	51.12^{a}	1.12^{a}	2.01^{a}	10.95^{a}	12.77^{a}
	20-40	28.97^{ab}	35.70^{a}	0.92^{ab}	1.43^{a}	10.96^{a}	13.28^{a}
	40-60	25.44^{b}	34.40^{a}	0.80^{b}	1.26^{a}	10.42^{a}	13.31^{a}
	LSD	5.50	18.37	0.21	1.50	1.04	1.69
Chemical fertilizer + crop residue retention	0-20		36.10^{a}		1.25^{a}		12.31^{a}
	20-40		32.12^{a}		1.06^{ab}		12.85^{a}
	40-60		22.77^{b}		0.93^{b}		12.81^{a}
	LSD$_{0.05}$		7.88		0.24		1.43

SOC stocks-Soil organic carbon; TOC- Total organic carbon; C/N- Carbon Nitrogen Ratio. Means with different letters down the column are statistically different at $P < 0.05$.

Effect of manure in combination with chemical fertilizer on SOC stocks, TOC and CN ratio down the depth

Chemical fertilizer combined with manure showed significant difference down the depth with SOC stocks at 0-20 cm depth being significantly different from 40-60 cm depth in Mukuyu. TOC was significantly different down the depth with TOC at 0-20 cm depth being significantly different from 20-40 cm and 40-60 cm depth in Mukuyu. CN ratio was significantly different down the depth in Shikomoli with 0-20 cm depth being significantly different from 20-40 cm and 40-60 cm depth (Table 6).

Table 6. Effect of management practices on SOC stocks. TOC and CN ratio down the soil profile

Management	Depth (cm)	SOC (Mg/ha)		TOC (%)		C/N	
		Shikomoli	Mukuyu	Shikomoli	Mukuyu	Shikomoli	Mukuyu
Chemical fertilizer	0-20	27.53^a	39.18^a	0.90^a	1.36^a	10.19a	12.43^a
	20-40	24.32^a	33.65^b	0.76^a	1.12^b	9.66a	12.98^a
	40-60	22.93^a	30.10^b	0.71^a	1.01^b	9.42^a	13.24^a
	LSD	10.59	5.08	0.34	0.18	0.86	0.91
Manure + chemical fertilizer	0-20	24.03^a	39.57^a	0.78^a	1.44^a	10.62^a	12.50^a
	20-40	21.90^a	34.23^{ab}	0.69^a	1.15^b	10.07^b	12.95^a
	40-60	21.09^a	30.01^b	0.67^a	0.99^b	9.88^b	12.95^a
	LSD	4.01	5.55	0.13	0.26	0.53	0.81
Chemical fertilizer +manure + crop residue retention	0-20	32.66^a	51.12^a	1.12^a	2.01^a	10.95^a	12.77^a
	20-40	28.97^{ab}	35.70^a	0.92^{ab}	1.43^a	10.96^a	13.28^a
	40-60	25.44^b	34.40^a	0.80^b	1.26^a	10.42^a	13.31^a
	LSD	5.50	18.37	0.21	1.50	1.04	1.69
Chemical fertilizer + crop residue retention	0-20		36.10^a		1.25^a		12.31^a
	20-40		32.12^a		1.06^{ab}		12.85^a
	40-60		22.77^b		0.93^b		12.81^a
	LSD$_{0.05}$		7.88		0.24		1.43

SOC stocks-Soil organic carbon; TOC- Total organic carbon; C/N- Carbon Nitrogen Ratio. Means with different letters down the column are statistically different at $P < 0.05$.

Effect of manure in combination with chemical fertilizer and crop residue retention on SOC stocks, TOC and CN ratio down the depth

In Shikomoli, manure combined with chemical fertilizer and crop residue retention had a significant difference down the depth with SOC stocks at 0-20 cm depth being significantly different from 40-60 cm depth. Significant effect was observed on TOC down the depth in Shikomoli with 0-20 cm depth being significantly different from 40-60 cm (Table 3.6).

Table 6. Effect of management practices on SOC stocks. TOC and CN ratio down the soil profile

Management	Depth (cm)	SOC (Mg/ha)		TOC (%)		C/N	
		Shikomoli	Mukuyu	Shikomoli	Mukuyu	Shikomoli	Mukuyu
Chemical fertilizer	0-20	27.53^{a}	39.18^{a}	0.90^{a}	1.36^{a}	10.19a	12.43^{a}
	20-40	24.32^{a}	33.65^{b}	0.76^{a}	1.12^{b}	9.66a	12.98^{a}
	40-60	22.93^{a}	30.10^{b}	0.71^{a}	1.01^{b}	9.42^{a}	13.24^{a}
	LSD	10.59	5.08	0.34	0.18	0.86	0.91
Manure + chemical fertilizer	0-20	24.03^{a}	39.57^{a}	0.78^{a}	1.44^{a}	10.62^{a}	12.50^{a}
	20-40	21.90^{a}	34.23^{ab}	0.69^{a}	1.15^{b}	10.07^{b}	12.95^{a}
	40-60	21.09^{a}	30.01^{b}	0.67^{a}	0.99^{b}	9.88^{b}	12.95^{a}
	LSD	4.01	5.55	0.13	0.26	0.53	0.81
Chemical fertilizer +manure + crop residue retention	0-20	32.66^{a}	51.12^{a}	1.12^{a}	2.01^{a}	10.95^{a}	12.77^{a}
	20-40	28.97^{ab}	35.70^{a}	0.92^{ab}	1.43^{a}	10.96^{a}	13.28^{a}
	40-60	25.44^{b}	34.40^{a}	0.80^{b}	1.26^{a}	10.42^{a}	13.31^{a}
	LSD	5.50	18.37	0.21	1.50	1.04	1.69
Chemical fertilizer + crop residue retention	0-20		36.10^{a}		1.25^{a}		12.31^{a}
	20-40		32.12^{a}		1.06^{ab}		12.85^{a}
	40-60		22.77^{b}		0.93^{b}		12.81^{a}
	$LSD_{0.05}$		7.88		0.24		1.43

SOC stocks-Soil organic carbon; TOC- Total organic carbon; C/N- Carbon Nitrogen Ratio. Means with different letters down the column are statistically different at $P < 0.05$.

Effect of chemical fertilizer in combination with crop residue retention on SOC stocks, TOC and CN ratio down the depth

A significant effect on TOC down the depth with 0-20 cm depth being significantly different from 40-60 cm depth (Table 3.6).

Table 6. Effect of management practices on SOC stocks. TOC and CN ratio down the soil profile

Management	Depth (cm)	SOC (Mg/ha)		TOC (%)		C/N	
		Shikomoli	Mukuyu	Shikomoli	Mukuyu	Shikomoli	Mukuyu
Chemical fertilizer	0-20	27.53^a	39.18^a	0.90^a	1.36^a	10.19a	12.43^a
	20-40	24.32^a	33.65^b	0.76^a	1.12^b	9.66a	12.98^a
	40-60	22.93^a	30.10^b	0.71^a	1.01^b	9.42^a	13.24^a
	LSD	10.59	5.08	0.34	0.18	0.86	0.91
Manure + chemical fertilizer	0-20	24.03^a	39.57^a	0.78^a	1.44^a	10.62^a	12.50^a
	20-40	21.90^a	34.23^{ab}	0.69^a	1.15^b	10.07^b	12.95^a
	40-60	21.09^a	30.01^b	0.67^a	0.99^b	9.88^b	12.95^a
	LSD	4.01	5.55	0.13	0.26	0.53	0.81
Chemical fertilizer +manure + crop residue retention	0-20	32.66^a	51.12^a	1.12^a	2.01^a	10.95^a	12.77^a
	20-40	28.97^{ab}	35.70^a	0.92^{ab}	1.43^a	10.96^a	13.28^a
	40-60	25.44^b	34.40^a	0.80^b	1.26^a	10.42^a	13.31^a
	LSD	5.50	18.37	0.21	1.50	1.04	1.69
Chemical fertilizer + crop residue retention	0-20		36.10^a		1.25^a		12.31^a
	20-40		32.12^a		1.06^{ab}		12.85^a
	40-60		22.77^b		0.93^b		12.81^a
	$LSD_{0.05}$		7.88		0.24		1.43

SOC stocks-Soil organic carbon; TOC- Total organic carbon; C/N- Carbon Nitrogen Ratio. Means with different letters down the column are statistically different at $P < 0.05$.

3.5 Discussion

3.5.1 Sociodemographic and biophysical characteristics

High number of female respondents in both sites indicate that the women are mainly left to manage the fields while their male counterpart look for other sources of income away from the farm. Thus, the women mainly influence the operations of the farms and consequently the management practices adopted and ultimately affect the soil fertility and food security. Similarly, Diiro *et al*. (2018) reported high participation of female in land decision compared to the male in western Kenya. In both sites the majority of respondents had basic education.

The level of education affects the uptake and implementation of new ideas, as those with education tend to take up new ideas quickly compared to those with no education. Hence, this will affect with adoption of management practices that improve SOC stocks. This is in agreement with Adolwa (2012) where it was reported that the literacy level affected access to information, understanding and adoption of the recommended technologies. Majority of the farmers were old as the young population shun from farming and look for other sources of income leaving the older population to do farming. This influences the adoption of certain management practices that could improve SOC stocks such as measures to control soil erosion since their uptake is greatly influenced by labour availability. In older population labour availability is limited and thus negatively impacts the uptake of best management practices. Similarly, Akinola *et al*. (2019) reported young population have a lower tendency of doing farming and prefer other sources of income. The small land sizes were due to high population in both sites. Increased population causes land sizes to be smaller because of subdividing land into smaller parcels of land. Smaller parcels of land affect soil fertility by influencing practices such as intercropping and agroforestry associated with increasing and sustaining SOC stocks. Chikowo *et al.* (2014) who found similar result, noting that farmers with had small parcels of land tend not to adopt agroforestry and intercropping practices. In both sites, the experience of slight erosion was attributed to the slope. The steeper the slope the higher the erosion rate (Misiko *et al.*, 201l). In both sites majority of the farms had livestock. The amount of manure applied and the amount of crop residue left on the fields are affected by the availability of livestock. Similar finding was reported by Giller *et al*. (2011) in western Kenya where it was found that farms with livestock tend to apply manure because of the availability.

3.5.2 Farms agricultural management practices

Management activities taken up by farmers included use of chemical fertilizer alone (F), chemical fertilizer + manure (FM), chemical fertilizer + crop residue retention (FC) and chemical fertilizer + manure + crop residue retention (FMC). In both sites, the main practice was use of manure combined with chemical fertilizer. This is because crop residue is given to livestock, which produces manure, which is returned to the soil. Manure is mainly used because it is readily available and added with fertilizer to improve soil fertility (Njoroge *et al.*, 2019). Further, since chemical fertilizer is mainly applied in small quantities, manure is added to compensate for the inadequacy of chemical fertilizer. Castellanos-Navarrete *et al.* (2015) found a similar result in western Kenya, with farmers using manure as an alternative input to increase soil fertility and chemical fertilizer as a complementary nutrient substitute.

3.5.3 Land use history and management for the past three years before the year of study

The use of hand hoe in Shikomoli and tractor and animal traction in Mukuyu was affected by land sizes and resources availability. Farmers with large land size tend to use larger tools compared to farmers with small land sizes. Further, the availability of resources influences the purchase power of the equipment to be used in tillage. Manure application of the majority of farmers in both sites was attributed to the ownership of livestock. Livestock ownership influences the availability of manure since farmers with livestock have higher chances of applying manure. Bationo *et al.* (2006) found out that more manure was applied in the region compared to crop residue retention because of competing uses for crop residue. The majority of the farmers in Shikomoli in both sites were intercropping maize and beans as opposed to other crops because maize and beans are the main cash crops and mainly used for subsistence. This was in line with a study conducted by Lee (2017) in western Kenya, which found maize and beans to be the most commonly cultivated crops.

The majority of farmers in both locations used chemical fertilizers, though at lower rates than the recommended 60 kg N/ha and 30 kg P/ha (FAO and ITPS, 2015; Mugwe *et al.*, 2009). Uptake of agroforestry in both sites was still very low because of small land sizes and high labour requirements and this was in agreement with Kuyah *et al.* (2017) and Place *et al.* (2003) who was working on the adoption of erosion control measures. Not all the farms retained crop residue because most farmers use crop residues as animal feed, fuel and building material. Njoroge *et al.*

(2019) and Musinguzi *et al*. (2013) found similar findings in which low retention of residue was attributed to competing needs for the resources such as livestock feed, fuel, building material.

3.5.4 Inputs applied and soil and water conservation measures

Majority of farms applied chemical fertilizer in both sites which was attributed to land sizes, availability of manure and income. Farmers with large land sizes tend to afford to apply chemical fertilizer. Also, chemical fertilizers are readily available as opposed crop residue and manure due to competing uses.

Chemical fertilizer has been reported to the main nutrient source among smallholder systems (Waswa and Kihara, 2014). The primary method of application for fertilizers was incorporation during planting and topdressing after crop emergence. This was attributed to the type of fertilizer used. Misiko *et al*. (2011) also reported that fertilizer type affected application method for example, DAP (Diammonium phosphate) fertilizer is mainly incorporated while CAN (Calcium ammonium nitrate) fertilizer is top-dressed. Erosion control measures, including trenches and grass strips, were practiced. This is because most of the farms had planted grass strips along the trenches for livestock feed. The adoption of these two practices were related. Similarly, Sileshi *et al*. (2019) reported that the soil erosion control measures were interrelated. However, support from government and agricultural officers to strengthen the adoption of other measures is necessary.

3.5.5 Correlation of management practices with SOC stocks in Shikomoli and Mukuyu

Shikomoli

A positive correlation between crop residue and SOC stocks indicated the importance of retaining crop residue. Retention of crop residue increases SOC stocks by increasing water availability through increased infiltration, nutrient content, reducing surface evaporation and increasing organic matter through decomposition. According to Raffa *et al*. (2015), crop residue retention increased SOC stocks due to higher organic matter content. Land size and SOC indicated negative correlation implying that as the land size increases, SOC content decreases. This is because the large land size would demand more carbon input, which smallholder farmers might not be able to access, thus less organic matter addition. Further, large land size implies heavy machinery that compacts soils, inhibits microbial decomposition, water infiltration, and ultimately negatively affects biomass production. According to Soracco *et al*. (2015), heavy machinery use decreased SOC stocks due to compaction and reduced aggregate stability.

Mukuyu

Negative correlation between the tillage method used and SOC was found implied that as the disturbance of the soil is increased through tillage method, it lowers SOC stocks through increased decomposition. Intensive tillage accelerates SOC loss through the breakdown of soil aggregates thereby increasing soil organic matter decomposition (Touré *et al*., 2013; Bationo *et al*., 2006).

The results revealed a positive correlation between erosion control practices and SOC down the depths. This implied that SOC stocks increased at each subsequent depth as more erosion control practices were put in place. Increased soil erosion control measures reduced erosion rate thus less SOC lost from the soil. Mahajan *et al*. (2020) obtained a similar result, in which erosion control measures increased SOC stocks at each depth due to a lower erosion rate. The upper depths, on the other hand, had higher SOC stocks than the lower depths.

3.5.6 Effect of Agricultural management practices on SOC stocks and total organic carbon (TOC)

The highest SOC stocks were found in both sites when fertilizer, manure, and crop residue were combined. This may be attributed to high organic matter concentration. Further, the inputs enhanced biomass production thus more carbon returned to the soil. However, Mukuyu showed higher values than Shikomoli, which was attributed to the soil texture and slope. Shikomoli had higher sand content than Mukuyu hence more SOC stocks lost through accelerated decomposition. In addition, higher carbon stocks in Mukuyu compared to Shikomoli was attributed to a relatively flat surface in Mukuyu than Shikomoli hence less loss of SOC stocks through erosion. When chemical fertilizer, crop residue, and manure were added, Paul *et al*. (2015) and Berazneva *et al*. (2014) recorded higher SOC stocks, which was close to our findings.

Effect of chemical fertilizer on SOC stocks and TOC down the depth

A significant effect of chemical fertilizer on SOC stocks and TOC down the depth in Mukuyu was found. This could be because of the amount of biomass produced and the decomposition process. Chemical fertilizer application affects the amount of biomass produced as application of fertilizer influence productivity. In addition, the application of chemical fertilizer enhances the decomposition process. Similarly, Poeplau *et al*. (2017) reported differences in SOC stocks due to chemical fertilizer application with a distinct increase in SOC stocks.

Effect of manure in combination with chemical fertilizer on SOC stocks, TOC and CN ratio down the depth

In Mukuyu, manure in combination with chemical fertilizer showed significant effect on SOC stocks, TOC and CN ratio down the depth. The differences could be due to amount of organic matter content as more carbon inputs are added to the soil from biomass and manure.

This was in agreement with Maltas *et al*. (2018), where it was reported an increase in carbon stocks at the surface was due to increased microbial activity and more carbon inputs.

Effect of chemical fertilizer in combination with crop residue retention on SOC stocks, TOC and CN ratio down the depth

Decline in SOC stocks down the depth because of limited inputs at lower depths. Inputs are mainly applied to upper layers, thus more concentration at the surface layers. This was in line with a study by Okeyo *et al*. (2016), where it was reported that inadequate inputs in smallholder systems resulted to variation in SOC. The significant impact of the management practices on SOC is in agreement with a study done in Ethiopia where management practices SOC, particularly in the upper layer (Gebeyehu and Soromessa, 2018). In addition, agronomic management practices influence SOC down the soil profile due to the amounts of carbon added (Don *et al*., 2009)

3.6 Conclusions and Recommendations

Manure in combination with chemical fertilizer was the most prevalent management method at both sites. When manure was used in combination with chemical fertilizer and crop residue retention, higher carbon stocks were observed. The correlation study revealed that in Shikomoli crop residue retention, land size and slope of the land were the main determinants of SOC stocks while in Mukuyu, tillage method and soil water conservation measures were the main factors governing SOC stocks. To enhance SOC stocks among smallholder farmers in both sites best management practices include combination of manure, fertilizer and crop residue retention.

CHAPTER FOUR: EXPLAINING THE VARIABILITY OF SOIL ORGANIC CARBON IN SMALLHOLDER FARMING SYSTEMS OF WESTERN KENYA

4.1. Abstract

Soil organic carbon (SOC) is an essential component in governing provision of critical ecosystem services, soil health and crop productivity. In addition, soil physicochemical properties strongly interact to influence SOC. However, paucity of information exists on how particular soil physical and chemical properties affect SOC stocks down the depth. The aim of this study was to investigate the influence of the physical and chemical properties on SOC down the depth in two villages in Shikomoli and Mukuyu, Western Kenya. Soil samples were collected from three subsequent depths (0-20 cm, 20-40 cm and 40-60 cm) from farmers under different management practices. The soil samples were analyzed for total nitrogen (TN), total organic carbon (TOC), silt, clay, sand, pH, available phosphorus (P), cation exchange capacity (CEC), bulk density (BD), exchangeable aluminium (Al), zinc (Zn), copper (Cu), iron (Fe), manganese (Mn) and aggregate stability (AS). The SOC stocks was calculated by multiplying the bulk density, TOC and depth of the soil. The study shows SOC stocks at 0-20 cm depth was significantly different from 40-60 cm depth in the two sites. In Shikomoli, the surface layer (0-20 cm), SOC stocks was 26.9 Mg C ha^{-1} while the lowest SOC stocks of 22. 6 Mg C ha^{-1} was observed at 40-60 cm depth. In Mukuyu, the surface layer (0-20 cm), SOC stocks was 40 Mg C ha^{-1} while SOC stocks of 30.1 Mg C ha^{-1} was observed at 40-60 cm depth. At both sites, SOC stocks decreased down the depth. Correlation analysis for both sites showed that TN, carbon to nitrogen ratio, silt, clay and Mn had a positive correlation, while sand and bulk density had a negative correlation with SOC. The study showed that to enhance SOC stocks among smallholder farmers, management practices that increase nitrogen content, available phosphorus, cation exchange capacity, geometric mean diameter, and mean weight diameter for soil aggregates' stability are important.

Keywords: Soil organic carbon stocks, Physical properties, Chemical properties

4.2. Introduction

Soil organic carbon (SOC) plays an important role in governing provision of critical ecosystem services, soil quality and productivity in terms of crop yields (Kane, 2015; Musinguzi *et al*., 2016). It increases nutrient uptake, water holding capacity, soil aeration, buffer capacity, microbial population and soil aggregate stability (Lal, 2016; Adhikari and Bhattacharyya, 2015). However SOC content is influenced by the strong interaction with physicochemical properties (Rahangdale *et al*., 2018).

Physical factors include bulk density and soil texture and aggregate stability. Bulk density strongly correlates with SOC and mainly influenced by soil texture (Nyberg *et al*., 2012). Increase in SOC stocks lowers bulk density (Chaudhari *et al*., 2013). Smallholder systems have low SOC due to high bulk density (Nwaogu *et al*., 2018). This is contributed by increased compaction as a result of cultivation, erosion, aggregate instability (Paul *et al*., 2015; Nyberg *et al*., 2012). Soil texture influences organic matter decomposition thus affect SOC levels and carbon sequestration potential (Singh *et al*., 2018; Kimetu *et al*., 2008). Clay and silt soils have high SOC content because they protect SOC from decomposition and has high association of organic matter on mineral surfaces *(* Poeplau *et al*., 2017; Mujuru *et al*., 2016). Sandy soils having less SOC (Musinguzi *et al*., 2013) due to low nutrient content, poor aggregate stability, reduced water holding capacity and organic matter association on mineral surfaces (Nyberg *et al*., 2012; Saiz *et al*., 2012). Sandy soils have been reported to have as low as 1% SOC content (Albrecht *et al*., 2005).

Chemical properties that influence SOC content include phosphorus, carbon to nitrogen ratio, nitrogen, cation exchange capacity, exchangeable aluminium, pH, and micronutrients. Phosphorus is a crucial nutrient required for growth of roots and elongation (Ratnayake *et al*., 2014; Ahmed *et al*., 2005). However, it is deficient among smallholder farmers due to microbial fixation, high aluminium content, unbalanced application of mineral fertilizer and long period of cultivation (Musinguzi *et al*., 2016; Moebius-Clune *et al*., 2011). Phosphorus content affects SOC stocks with high phosphorus concentration resulting to increased SOC stocks though increased biomass production (Njoroge *et al*., 2019). Carbon to nitrogen ratio is important in governing decomposition and ultimately SOC stocks with high C/N lowering decomposition rate and vice versa (Gebeyehu and Soromessa, 2018; Musinguzi *et al*., 2013). SOC and nitrogen are highly associated (Gebeyehu and Soromessa, 2018).

Nitrogen content influences organic matter decomposition, which in turn promotes the different organic matter fractions (Waswa *et al*., 2007). Cation exchange capacity affects the availability of nutrients in soils (Schweizer *et al*., 2018). Low cation exchange capacity lowers the SOC because of reduced capacity of the soil to store carbon (Pal and Marschner, 2016). High levels of exchangeable aluminum in the soils increases SOC content by stabilizing organic carbon through binding of organic matter (Tsozué *et al*., 2019). Soil pH is an important parameter that affects the soil fertility by determining the solubility and availability of nutrients (Kabirinejad *et al*., 2014). Soil pH influences the SOC stocks and increases its concentration especially at near-neutral pH because of increased microbial activity (Benbi and Brar, 2009). Micronutrients are important in the soil since they improve soil and crop productivity though they are required in small quantities compared to macronutrients. Most soils in western Kenya have micronutrient deficiency particularly copper and zinc (Njoroge *et al*., 2017). Micronutrient concentration in the soil is mainly affected by pH (Kabirinejad *et al*., 2014; Rutkowska *et al*., 2014). They influence SOC levels by controlling the biomass productivity which in turn controls the proportion of crop residue remaining in the farms (Kabirinejad *et al*., 2014; Rutkowska *et al*., 2014; Shah & Andrabi, 2009). The aim of this study was to see how SOC differed depending on depth and physicochemical properties in small-scale farms in western Kenya.

4.3. Materials and methods

4.3.1 Description of the study site

The study was carried out in Mukuyu and Shikomoli villages in western Kenya as described in chapter three section 3.3.2.

4.3.2. Soil sampling and analysis

Soil samples were obtained from the selected categories of farms within a quadrat. A plot which has been under maize cultivation for more than 10 years was identified per farmer making a total of 60 plots. The size of the quadrat depended on the size of the plot per farmer. Within each quadrat of every plot, five spots were randomly selected, and samples collected at three subsequent depth 0-20 cm, 20-40 cm and 40-60 cm. Composite samples of about 500 g were collected at each depth in each plot. 3 samples were taken from each plot, totalling 180 samples for the 60 farms. Bulk density was measured by collecting sample using cylindrical core ring at each subsequent depth from the middle of the plot.

Geographical position and elevation were also be recorded using a geographical position system (GPS) device. Soil samples collected were then taken to the laboratory for analysis.

Physical soil analysis: Bulk density was determined by oven drying at 105 ^{0}C for 48 hours to a constant weight (Blake, 1965). Bulk density (g/cm^{3}) was determined as a ratio between dry weight of the soil and volume of soil core.

Chemical Soil analysis: Soil samples were air-dried, grounded and 2mm sieved and weighed. Analysis of soil texture was done using the Bouyoucos hydrometer method by dispersing the soil with sodium hexa-metaphosphate (Day, 1956). Soil pH (H_20) was measured in a 1:2 soil: water suspension with a glass electrode. Cation exchange capacity was determined using Metson (1961) method. Available phosphorus and micronutrients was extracted using the standard Mehlich-1 (M1) extraction method (1953). Available phosphorus was determined calorimetrically on spectrophotometer while micronutrients was determined using Atomic Absorption Spectrophotometer (AAS). Exchangeable aluminium was determined by titration (McLean 1965). Total carbon and total nitrogen was analysed using A C/N elemental analyser (Macro Cube, Elementar GmbH, Germany) through oxidation. The concentration then translates to organic carbon and organic nitrogen (Sommer *et al*., 2018). Soil organic carbon stocks was determined by multiplying measured total SOC, bulk density equation and the individual depth (Poeplau and Don, 2015)

Wet sieving method was used to determine aggregate stability using Cambardella & Elliott (1993) procedure. The method involved drying the soil samples for 48 hours before passing them through 8 mm sieve. The soils were oven dried at 60 °C for 24 hours and 32 g of soil submerged (in water) in a wet sieving apparatus (Eijkelkamp 08.13) for 5 minutes to allow for slaking. Sieving of the samples was done concurrently using a 2000, 250 and 53 µm sieves for 3 minutes each to obtain large macro-aggregates, small macro-aggregates and micro-aggregates fractions, respectively. The filtrate (silt +clay) and other aggregate fractions obtained were oven dried at 60 ° C for 48 hours and weights recorded. Mean weight diameter (MWD) was calculated using equation (1) by (Cambardella & Elliott, 1993).

$$\mathrm{MWD} = \Sigma \mathrm{X}i\mathrm{W}i \qquad \text{(Equation 1)}$$

Where: Xi= diameter of the ith sieve size and Wi= proportion of total aggregates in the ith fraction

Geometric mean diameter (GMD) of the different aggregate fractions was calculated using equation (2) by Six et al. (2000).

$$\text{GMD} = \frac{\Sigma \text{Wi} \ln \text{Xi}}{\Sigma \text{Wi}} \qquad \text{(Equation 2)}$$

Where Wi= weight of aggregates in size class i and Xi= mean diameter of the class size

4.3.4. Data Analysis

All statistical analysis was performed using R software version 3.5.1. Analysis of Variance (ANOVA) and Pearson correlation was used in data analysis. The variations in soil properties between the two sites according to sampled depths were calculated using ANOVA. The means were separated using Fishers least significant difference (LSD). A correlation was done to relate SOC concentrations to other soil properties and among the properties themselves. Prior to correlation analysis of soil properties, the data was log-transformed except for pH for standardization. The statistical significance was determined at $P < 0.05$.

4.4. Results

4.4.1. Soil organic carbon down the soil profile (0-60 cm)

The surface layer (0-20 cm) had the highest SOC stocks at 26.91 Mg C ha^{-1} while the lowest SOC stocks of 22.56 Mg C ha^{-1} was observed at 40-60 cm depth in Shikomoli (Table 4.1). SOC stocks at 0-20 cm depth was significantly different from 40-60 cm depth.

The surface layer (0-20 cm) had the highest SOC stocks at 40.01 Mg C ha^{-1} while the lowest SOC stocks of 30.11 Mg C ha^{-1} was observed at 40-60 cm depth in Mukuyu (Table 4.1). SOC stocks were significantly different at each depth. Generally, Mukuyu had the highest SOC stocks compared to Shikomoli with SOC stocks decreasing down the depth in both sites.

Table 7. SOC stocks down the soil profile for both sites

	SOC Stocks (Mg/ha)	
Depth (cm)	**Shikomoli**	**Mukuyu**
0-20	26.91^{a}	40.01^{a}
20-40	24.17^{ab}	33.83^{b}
40-60	22.56^{b}	30.11^{c}

Note; means with different letters are statistically significant across a row (p < 0.05)

4.4.2. Soil profile description of physical and chemical properties to a depth of 60 cm

The physical and chemical properties in both sites according to depth are shown in table 4.2. Results indicated a significant difference between total nitrogen in both sites except at 40-60 cm depth. In addition, SOC stocks, CN ratio, clay, sand, bulk density, CEC, zinc, exchangeable aluminum, large macro-aggregates, and small macro-aggregate were significantly different at all depths and in both sites. Further, results indicated a significant difference between pH and available phosphorus in both sites at 40-60 cm depth ($P < 0.05$).

The micro-aggregate was significantly different between the two sites at 0-20 cm depth, with Mukuyu having a higher micro-aggregate fraction than Shikomoli at all depths. The silt and clay were significantly different between the two sites at 0-20 cm depth. The mean weight diameter was significantly different between the two sites at 20-40 cm and 40-60 cm depth. Results showed that geometric mean diameter was significantly different between the two sites at 40-60 cm

Table 8. Soil physicochemical properties according to site and depth.

	Depth (cm)											
	0-20				20-40				40-60			
Soil properties	**Shikomoli**	**Mukuyu**	**Mean**	**LSD$_{0.05}$**	**Shikomoli**	**Mukuyu**	**Mean**	**LSD$_{0.05}$**	**Shikomoli**	**Mukuyu**	**Mean**	**LSD$_{0.05}$**
TN (%)	0.08^b	0.11^a	0.10	0.01	0.07^b	0.09a	0.08	0.009	0.07^a	0.08^a	0.07	0.008
TOC (%)	0.89^b	1.44^a	1.16	0.19	0.76^b	1.15^a	0.96	0.12	0.71^b	1.01^a	0.86	0.11
C/N	10.64^b	12.47^a	11.55	0.37	10.24^b	12.97^a	11.61	0.53	9.95^b	13.06^a	11.50	0.49
SOC (Mg/ha)	26.91^b	40.01^a	33.46	4.15	24.17^b	33.83^a	29.00	2.98	22.56^b	30.11^a	26.33	2.75
pH	5.67^a	5.85^a	5.76	0.22	5.56^a	5.75^a	5.65	0.24	5.54^b	5.81^a	5.68	0.23
Clay (%)	23.04^b	36.38^a	29.71	2.88	27.37^b	44.71^a	36.04	3.25	30.46^b	47.60^a	39.03	3.51
Sand (%)	6.77^a	53.29^b	60.53	3.78	64.18^a	47.96^b	56.07	3.58	61.41^a	45.51^b	53.46	3.65
Silt (%)	9.19^a	10.34^a	9.76	2.31	8.46^a	7.34^a	7.90	1.93	8.12^a	6.90^a	7.51	1.73
BD (g/cm^3)	1.52^a	1.42^b	1.47	0.06	1.58^a	1.40^b	1.54	0.06	1.60^a	1.50^b	1.55	0.06
P (ppm)	27.94^a	26.40^a	27.17	8.44	21.18^a	20.55^a	20.86	6.56	21.89^a	15.33^b	18.61	6.48
CEC (cmol/kg)	6.18^b	9.28^a	7.73	1.76	5.73^b	9.94^a	7.83	1.81	5.77^b	8.81^a	7.29	1.55
Zinc (ppm)	10.01^a	5.44^b	7.72	2.94	6.92^a	3.59^b	5.25	2.19	5.86^a	3.54^b	4.70	1.59
Mn (ppm)	41.54^a	36.45^a	38.99	7.86	29.22^a	20.47^b	24.84	7.23	25.35^a	16.99^b	21.17	6.68
Iron (ppm)	36.46^a	60.47^a	48.46	25.39	30.45^a	53.85^a	42.15	25.72	31.26^a	44.72^a	37.99	23.34
Copper (ppm)	0.48^a	0.66^a	0.57	0.33	0.19^b	0.55^a	0.37	0.25	0.29^a	0.47^a	0.38	0.27
Al (cmol/kg)	0.45^a	0.30^a	0.38	0.22	0.43^a	0.39^a	0.41	0.25	0.57^a	0.37^a	0.47	0.33
LM	7.51^a	12.40^a	9.96	5.12	6.63^b	15.17^a	10.90	6.51	6.28^b	18.11^a	12.20	7.63
SM	63.09^a	44.96^b	54.02	3.87	68.50^a	57.59^b	63.05	4.90	69.15^a	56.26^b	62.71	5.31
M	23.07^b	33.94^a	28.50	3.26	20.69^a	23.47^a	22.08	3.98	20.09^b	21.89^a	20.99	3.65
S+C	5.72^b	8.24^a	6.98	1.34	3.58^a	3.51^a	3.55	0.99	4.05^a	3.44^a	3.74	1.00
MWD	1.13^a	1.18^a	1.16	0.23	1.14^b	1.45^a	1.29	0.29	1.13^b	1.58^a	1.35	0.33
GMD	0.62^a	0.55^a	0.59	0.17	0.70^a	0.86^a	0.78	0.20	0.70^b	0.95^a	0.83	0.23

TN = total nitrogen, TOC = total organic carbon, C/N = carbon to nitrogen ratio, SOC = soil organic carbon, BD = Bulk density, P = available phosphorus, Al = exchangeable aluminium, Mn = manganese, LM = large macro-aggregate, SM = small macro-aggregate, M = micro-aggregate, S + C = silt and clay, MWD = mean weight diameter, GMD = geometric mean diameter. Note; means with the same letters in each depth are not significantly different ($P < 0.05$)

4.3 Relationship between soil physiochemical properties and SOC dynamics

Correlation between SOC stocks and other soil properties for Shikomoli

The Pearson correlation coefficients are summarized for all the subsequent depths (0-20 cm, 2-40 cm and 40-60 cm) in table 4.3, table 4.4 and table 4.5. Significant positive correlation of clay with SOC stocks was observed at all sampled depths. At all depths sampled, positive correlation of manganese with SOC stocks was observed. A significant positive correlation of cation exchange capacity with SOC stocks was found at sub surface layer (20-40 cm). Significant negative correlation of sand with SOC stocks at all sampled depths. Significant negative correlation of bulk density with SOC stocks was observed at the subsurface layer (40-60 cm).

Table 9. Pearson correlation matrix for (0-20 cm) depth for Shikomoli ($P < 0.05$)

	OC	ON	C/N	SOC	PH	clay	sand	silt	BD	Available P	CEC	Zn	Mn	Fe	Cu	Exc. Al
	%			(Mg/ha)			%		g/cm^3	ppm	cmol/kg		ppm			cmol/kg
OC	1															
ON	0.98*	1														
C/N	0.37*	0.16	1													
SOC	0.97*	0.95*	0.33	1												
PH	0.16	0.08	0.42*	0.24	1											
clay	0.55*	0.68*	−0.41*	0.56*	−0.26	1										
sand	−0.59*	−0.69*	0.28	−0.56*	0.27	−0.91*	1									
silt	0.39*	0.36*	0.24	0.31	−0.01	0.26	−0.58*	1								
BD	−0.36	−0.33	−0.22	−0.12	0.24	−0.09	0.24	−0.41*	1							
Available P	0.03	−0.05	0.32	0.07	0.27	−0.36	0.39*	−0.34	0.15	1						
CEC	0.19	0.21	−0.04	0.12	−0.08	0.16	−0.25	0.39*	−0.31	−0.21	1					
Zn	0.22	0.13	0.4*	0.23	0.41*	−0.1	0.05	0.14	0	0.59*	0.17	1				
Mn	0.72*	0.75*	0.09	0.73*	0.02	0.58*	−0.53*	0.24	−0.15	0.03	0.1	0.3	1			
Fe	0.23	0.26	−0.04	0.24	−0.24	0.29	−0.14	−0.35	−0.04	0.53*	−0.23	0.22	0.29	1		
Cu	−0.19	−0.23	0.12	−0.2	0.2	−0.25	0.27	−0.14	−0.01	0.44*	−0.1	0.43*	−0.12	0.33	1	
Exc. Al	0.18	0.27	−0.35	0.16	−0.56*	0.38*	−0.36	0.06	−0.12	−0.3	−0.11	−0.3	0.24	0.22	−0.06	1

OC = total organic carbon, ON = total organic nitrogen, C/N = carbon to nitrogen ratio, SOC, soil organic carbon stocks, BD = bulk density, Available P = available phosphorus, CEC = cation exchange capacity, Zn = zinc, Mn= manganese, Fe = iron, Cu = copper, Exc. Al = Exchangeable aluminium

Table 10. Pearson correlation matrix for (20-40 cm) depth for Shikomoli ($P < 0.05$)

	OC	ON	C/N	SOC	PH	clay	sand	silt	BD	Available P	CEC	Zn	Mn	Fe	Cu	Exc. Al
		%		Mg ha^{-1}			%		g/cm^3	ppm	Cmol/kg			ppm		cmol/kg
OC	1															
ON	0.94*	1														
C/N	0.28	−0.06	1													
SOC	0.98*	0.92*	0.28	1												
PH	−0.04	−0.1	0.17	0.03	1											
clay	0.74*	0.85*	−0.24	0.72*	−0.39*	1										
sand	−0.73*	−0.83*	0.2	−0.67*	0.37*	−0.92*	1									
silt	0.3	0.3	0.02	0.17	−0.03	0.18	−0.51*	1								
BD	−0.06	−0.06	−0.02	0.14	0.31	−0.04	0.29	−0.59*	1							
Available P	−0.21	−0.25	0.09	−0.17	0.19	−0.34	0.43*	−0.39*	0.22	1						
CEC	0.43*	0.52*	−0.21	0.38*	−0.06	0.46*	−0.51*	0.33	−0.21	−0.14	1					
Zn	0.29	0.21	0.26	0.31	0.34	−0.09	0.11	0.04	0.11	0.35	−0.09	1				
Mn	0.73*	0.74*	0.06	0.73*	0.04	0.55*	−0.55*	0.21	0.04	−0.1	0.38*	0.22	1			
Fe	0.25	0.39*	−0.39*	0.26	−0.23	0.41*	−0.26	−0.16	0.09	0.46*	0.22	0.13	0.37*	1		
Cu	0.01	−0.05	0.16	0.08	0.56*	−0.28	0.39*	−0.37*	0.34	0.43*	−0.19	0.55*	0.2	0.14	1	
Exc. Al	−0.01	−0.14	0.37*	−0.04	−0.23	−0.14	0.17	−0.18	−0.17	0.03	0.02	0.03	−0.27	−0.11	0.04	1

OC = total organic carbon, ON = total organic nitrogen, C/N = carbon to nitrogen ratio, SOC, soil organic carbon stocks, BD = bulk density, Available P = available phosphorus, CEC = cation exchange capacity, Zn = zinc, Mn= manganese, Fe = iron, Cu = copper, Exc. Al = Exchangeable aluminium

Table 11. Pearson correlation matrix for (40-60cm) depth for Shikomoli ($P < 0.05$)

	OC	ON	C/N	SOC	PH	clay	sand	silt	BD	Available P	CEC	Zn	Mn	Fe	Cu	Exc. Al
		%		$Mgha^{-1}$			%		g/cm^3	ppm	cmol/kg			ppm		cmol/kg
OC	1															
ON	0.96*	1														
C/N	0.41*	0.13	1													
SOC	0.99*	0.92*	0.49*	1												
PH	−0.02	−0.11	0.29	0.07	1											
clay	0.61*	0.76*	−0.29	0.53*	−0.38*	1										
sand	−0.57*	−0.71*	0.28	−0.48*	0.37*	−0.94*	1									
silt	0.13	0.13	0.03	0.12	0.12	0.02	−0.27	1								
BD	−0.64*	−0.75*	0.16	−0.51*	0.41*	−0.74*	0.74*	−0.16	1							
Available P	−0.24	−0.22	−0.13	−0.19	0.12	−0.24	0.32	−0.42*	0.37*	1						
CEC	0.34	0.39*	−0.05	0.32	−0.03	0.31	−0.32	0.32	−0.34	−0.1	1					
Zn	−0.07	−0.1	0.07	−0.03	0.25	−0.32	0.34	−0.1	0.21	0.35	−0.1	1				
Mn	0.61*	0.66*	0	0.57*	−0.47*	0.63*	−0.62*	0.15	−0.55*	−0.08	0.27	−0.03	1			
Fe	0.04	0.12	−0.25	0.02	−0.33	0.3	−0.19	−0.37*	−0.13	0.51*	−0.1	−0.16	0.18	1		
Cu	0.25	0.19	0.26	0.29	−0.1	0.17	−0.14	−0.08	0.02	0.41*	0.16	−0.04	0.31	0.51*	1	
Exc. Al	0.07	0.15	−0.23	−0.01	−0.84*	0.31	−0.26	−0.29	−0.44*	−0.04	−0.1	−0.19	0.37*	0.27	0.02	1

OC = total organic carbon, ON = total organic nitrogen, C/N = carbon to nitrogen ratio, SOC, soil organic carbon stocks, BD = bulk density, Available P = available phosphorus, CEC = cation exchange capacity, Zn = zinc, Mn= manganese, Fe = iron, Cu = copper, Exc. Al = Exchangeable aluminium

Correlation between SOC stocks and other soil properties for Mukuyu

Table 4.6 table, 4.7 and table 4.8 shows the Pearson correlation coefficients summarized for all the subsequent depths (0-20 cm, 2-40 cm and 40-60 cm). At the surface layer, there was a significant negative correlation between sand and SOC stocks (0-20 cm). At the surface layer, there was a significant positive correlation between silt and SOC stocks (0-20 cm). At the surface (0-20 cm) and subsurface, there was a significant positive correlation between cation exchange capability and SOC stocks (20-40 cm Manganese stocks was found to have a significant positive correlation with SOC stocks at both the surface (0-20 cm) and subsurface levels (20-40 cm).

Table 12. Pearson correlation matrix for (0-20 cm) depth for Mukuyu ($P < 0.05$)

	OC	ON	C/N	SOC	PH	clay	sand	silt	BD	Available P	CEC	Zn	Mn	Fe	Cu	Exc. Al
		%		Mg ha^{-1}			%		g/cm^3	ppm	cmol/kg			ppm		cmol/kg
OC	1															
ON	0.98*	1														
C/N	0.69*	0.53*	1													
SOC	0.93*	0.87*	0.75*	1												
PH	0.18	0.29	−0.28	0.06	1											
clay	0.13	0.17	−0.05	0	0.35	1										
sand	−0.66*	−0.71*	−0.2	−0.4*	−0.52*	−0.56*	1									
silt	0.57*	0.6*	0.25	0.39*	0.42*	−0.11	−0.71*	1								
BD	−0.63*	−0.68*	−0.2	−0.29	−0.34	−0.34	0.83*	−0.63*	1							
Available P	−0.24	−0.24	−0.14	−0.18	−0.04	−0.16	0.21	−0.13	0.25	1						
CEC	0.77*	0.76*	0.48*	0.62*	0.33	0.29	−0.77*	0.66*	−0.66*	−0.21	1					
Zn	0.1	0.09	0.11	0.09	0.08	−0.28	−0.03	0.36	−0.07	0.06	0.01	1				
Mn	0.4*	0.4*	0.23	0.37*	0.21	0.02	−0.39*	0.44*	−0.23	0.02	0.34	0.27	1			
Fe	−0.32	−0.29	−0.32	−0.32	−0.22	−0.18	0.13	0	0.16	0.74*	−0.14	0.07	0.09	1		
Cu	−0.14	−0.1	−0.21	−0.27	−0.23	−0.05	−0.07	0.1	−0.2	0.19	−0.04	0.17	−0.03	0.51*	1	
Exc. Al	−0.21	−0.23	−0.02	−0.18	−0.67*	0	0.23	−0.35	0.15	0.05	−0.36*	−0.22	−0.29	0.26	0.23	1

OC = total organic carbon, ON = total organic nitrogen, C/N = carbon to nitrogen ratio, SOC, soil organic carbon stocks, BD = bulk density, Available P = available phosphorus, CEC = cation exchange capacity, Zn = zinc, Mn= manganese, Fe = iron, Cu = copper, Exc. Al = Exchangeable aluminium

Table 13. Pearson correlation matrix for (20-40 cm) depth for Mukuyu ($P < 0.05$)

	OC	ON	C/N	SOC	PH	clay	sand	silt	BD	Available P	CEC	Zn	Mn	Fe	Cu	Exc. Al
	%			Mg ha^{-1}			%		g/cm^3	ppm	Cmol/kg			ppm		Cmol/kg
% OC	1															
% ON	0.93*	1														
C/N	0.7*	0.38*	1													
SOC (Mg/ha)	0.85*	0.69*	0.79*	1												
PH	0.05	0.3	−0.46*	−0.19	1											
clay	0.15	0.16	0.06	0.06	0.1	1										
sand	−0.57*	−0.69*	−0.1	−0.23	−0.4*	−0.58*	1									
silt	0.36*	0.52*	−0.1	0.13	0.44*	−0.31	−0.53*	1								
BD	−0.62*	−0.72*	−0.14	−0.12	−0.37*	−0.21	0.75*	−0.5*	1							
Available P	0.1	0.12	0.01	0.13	0.13	−0.38*	0.18	0.13	0.02	1						
CEC	0.68*	0.74*	0.27	0.47*	0.41*	0.24	−0.67*	0.46*	−0.6*	0.13	1					
Zn	0.14	0.16	0.02	0.12	0.2	0.1	−0.04	−0.13	−0.08	−0.31	0.17	1				
Mn	0.52*	0.53*	0.28	0.5*	0.32	0.16	−0.45*	0.31	−0.24	0.26	0.52*	0.17	1			
Fe	0.14	0.18	0	0.12	0.07	−0.4*	0.09	0.21	−0.09	0.86*	0.17	−0.39*	0.25	1		
Cu	0.09	0.2	−0.16	−0.03	0.05	−0.31	−0.04	0.29	−0.22	0.51*	0.14	−0.32	0	0.62*	1	
Exc. Al	−0.2	−0.29	0.06	−0.01	−0.75*	−0.07	0.35	−0.37*	0.38*	0.02	−0.32	−0.19	−0.27	0.05	0.26	1

OC = total organic carbon, ON = total organic nitrogen, C/N = carbon to nitrogen ratio, SOC, soil organic carbon stocks, BD = bulk density, Available P = available phosphorus, CEC = cation exchange capacity, Zn = zinc, Mn= manganese, Fe = iron, Cu = copper, Exc. Al = Exchangeable aluminium

Table 14. Pearson correlation matrix for (40-60 cm) depth for Mukuyu (P < 0.05)

	% OC	% ON	C/N	SOC (Mg/ha)	PH	clay	sand	silt	BD	Available P	CEC	Zn	Mn	Fe	Cu	Exc. Al
% OC	1															
% ON	0.92*	1														
C/N	0.71*	0.39*	1													
SOC (Mg/ha)	0.85*	0.69*	0.77*	1												
PH	−0.12	0.15	−0.56*	−0.34	1											
clay	0.32	0.46*	−0.07	0.11	0.11	1										
sand	−0.46*	−0.65*	0.08	−0.06	−0.48*	−0.66*	1									
silt	0	0.11	−0.19	−0.16	0.55*	−0.32	−0.43*	1								
BD	−0.42*	−0.55*	−0.02	0.12	−0.36	−0.41*	0.76*	−0.29	1							
Available P	−0.17	−0.09	−0.26	−0.1	0.33	−0.35	0.14	0.28	0.15	1						
CEC	0.49*	0.45*	0.36*	0.23	0.14	−0.04	−0.46*	0.44*	−0.53*	−0.22	1					
Zn	−0.16	−0.19	−0.04	−0.03	0.08	−0.29	0.04	0.32	0.25	0.26	0.04	1				
Mn	0.46*	0.55*	0.1	0.36	0.47*	0.25	−0.48*	0.27	−0.25	0.03	0.26*	0.01	1			
Fe	−0.08	−0.01	−0.16	−0.01	0.19	−0.49*	0.26	0.22	0.12	0.58*	−0.13	0.14*	0.13	1		
Cu	0.13	0.2	−0.06	0.03	0.07	0.01	−0.13	0.14	−0.19	0.4*	0.04	−0.08	−0.02	0.5*	1	
Exc. Al	−0.35	−0.52*	0.1	−0.04	−0.59*	−0.12	0.55*	−0.42*	0.58*	−0.27	−0.35	−0.06	−0.54*	−0.24	−0.03	1

OC = total organic carbon, ON = total organic nitrogen, C/N = carbon to nitrogen ratio, SOC, soil organic carbon stocks, BD = bulk density, Available P = available phosphorus, CEC = cation exchange capacity, Zn = zinc, Mn= manganese, Fe = iron, Cu = copper, Exc. Al = Exchangeable aluminium

4.4.4 Correlation analysis between soil aggregate and SOC stocks

Results indicating the correlation between soil aggregates fractions and SOC stocks are represented in Table 4.9. However, the correlations between SOC stocks and soil aggregates is only significant for random depths.

Table 15. Correlation between soil aggregate fractions and soil organic carbon stocks

	Shikomoli			**Mukuyu**		
Aggregate fraction	**0-20 cm**	**20-40 cm**	**40-60cm**	**0-20 cm**	**20-40 cm**	**40-60 cm**
Large macro-aggregate	0.16	0.06	0.27	-0.37*	-0.23	0.03
Small macro-aggregate	0.24	0.17	0.04	0.26	0.08	0.17
Micro-aggregate	-0.37*	-0.26	-0.24	0.36	0.4*	0.25
Silt and clay	-0.39*	-0.34	-0.44*	0.15	0.32	0.1
Mean weight diameter	0.29	0.2	0.41*	-0.44*	-0.31	-0.08
Geometric mean diameter	0.36	0.4*	0.44*	-0.39*	-0.37*	-0.1

4.5 Discussion

4.5.1. Soil organic carbon down the depth (0-60 cm)

The SOC stocks decreased down the depth with the upper layer having higher SOC stocks compared to the sub-surface layers in both sites. The decrease in SOC stocks down the depth is because inputs in terms of organic matter are mainly applied on the surface thus lower depths receiving lower amounts leading to lower SOC stocks. The decrease in SOC stocks down the depth because of the surface application was consistent with results from Johannes et al. (2017); Ren *et al*. (2014) and Nyberg *et al*. (2012) where organic matter resulted to reduction in SOC stocks down the soil profile.

4.5.2. Soil profile description of physical and chemical properties to a depth of 60 cm

The significant difference between total nitrogen in Mukuyu and Shikomoli except at 40-60cm depth was because of different managements in terms of amount and quality of organic and inorganic resources applied. Okeyo *et al*. (2016) stated consistent outcome where differences in crop residue and chemical fertilizer application resulted to different nitrogen concentrations among farms. In addition, high quality of residues increases the nitrogen content in the soils and this was in agreement with Kätterer *et al*. (2019). Shikomoli had a lower nitrogen level and is attributed to sandy soils, which enhances decomposition and leaching of nutrients. In both sites, the surface layer (0-20 cm) has a higher concentration than the subsurface (20-40cm and 40-60cm) and this can be explained by the amount of inputs applied on the surface compared to subsurface layers. Ren *et al*. (2014) stated a similar conclusion where upper layer had the highest nitrogen content but it decreased down the depth due to organic matter additions mainly on the top layer. The average observed value of 0.10% was below the critical level of 0.2% established by NAAIAP and KARI, (2014); Landon, (1991) thus both sites had deficient nitrogen. Deficiency in nitrogen affect SOC stocks since they are highly associated, increase in nitrogen increases carbon concentration and affects the decomposition rate (Gebeyehu and Soromessa, 2018). Further, low nitrogen concentration negatively impacts carbon sequestration since for sequestration to occur, nitrogen content has to be be in sufficient quantities (Horwath and Kuzyakov 2018).

The variations in CN ratio values between sites and depths were due to the quality and quantity of organic inputs used, tillage, and soil physical properties.

According to Okeyo *et al*. (2016), variability in CN ratios was attributed to contrast in cultivation, quality of crop residue retained and bulk density. Also soil texture influences carbon to nitrogen ratio, increase in clay content increases the carbon to nitrogen ratio because clay contains more carbon content. Pal and Marschner (2016) reported similar finding where high CN ratio was attributed to high clay content in the soils. CN ratio influences soil organic matter decomposition and, ultimately SOC stocks (Gebeyehu and Soromessa, 2018). The decline in SOC stocks down the depth was mainly attributed to decline in organic matter content. The decline in SOC down the soil profile was also reported in western Kenya by Nyberg *et al*. (2012) and was attributed reduced organic matter content. This was also in agreement (Vågen *et al*., 2018). The observed values of 18.5 to 52.5 Mg ha^{-1} correspond to those reported for croplands (Brown *et al*., 2012).

Soil texture differences in both sites and depths was mainly influenced by parent material. However, in some cases cultivation affects soil texture particularly the clay content. Tillage caused a higher percentage of silt in both sites on the surface layer and this was consistent with study by (Musinguzi *et al*., 2015). Differences in bulk density could be because of texture, organic matter and tillage. Intensive tillage increases the bulk density due to the compaction of soils. A similar conclusion by Kätterer *et al*. (2019); Okeyo *et al*. (2016) and (Ngome *et al*. (2011) was observed where soil texture, different SOC levels and management practices played a critical role in influencing the bulk density. The decrease in available phosphorus down the depth could be as a result of phosphorus fixation at lower depths. The findings were consistent with those of Kisinyo *et al*. (2015) and Rahangdale *et al*., 2018 where available phosphorus decreased down the depth due to fixation. The observed values were lower than the critical value of 30 ppm thus deficient in both sites.

The differences of CEC with depth in both sites is attributed to organic matter content and soil texture. At lower layers, the organic matter content decreases thus reduced levels of CEC. In terms of texture, as depth increases the clay content decreases thus increase in cation exchange capacity. In addition, high weathering could be attributed to the low CEC values. According to Tittonell *et al*. (2010) and Lal (2006), lower CEC is mainly attributed to sandy soils and decline in organic matter. The observed values are lower than the critical limit of 15 cmol/kg thus, CEC is deficient in both sites. The differences in zinc content between sites and depth could be as a result of organic input into the soils since higher amount of organic input the higher the zinc content.

According to Zhang *et al*. (2015), manure and crop residue application resulted to high zinc content particularly on the upper layer. Zinc levels were above the threshold value of 5 ppm (NAAIAP and KARI, 2014) except for the sub-surface layers layer for Shikomoli, which were deficient. The observed values of manganese were above the critical limit of 25 ppm (Landon, 1991; Adeoye and Agboola, 1985)) thus considered sufficient in the soils. The iron level in both sites was > 10 ppm, which is considered the critical value (NAAIAP and KARI, 2014) thus, no deficiency of iron in the soil for both sites. The observed copper values were lower than the critical value of 1.0 ppm (NAAIAP and KARI, 2014) thus considered deficient. The differences in exchangeable aluminum levels were mainly attributed to pH since decline in pH increases the exchangeable aluminum concentration. Shikomoli had a lower pH compared to Mukuyu thus higher levels of exchangeable aluminum. This was consistent with a finding from Kisinyo *et al*. (2013) where acidic soils contribute to higher levels of exchangeable aluminum. The reported values in both sites are below the critical values of 2.0 cmol kg^{-1} above which is considered toxic to most crops (Landon, 1991).

Soil aggregate fractions were significantly different between sites and depth and this influenced the SOC stocks by affecting SOC stocks exposed to decomposition and the concentration adsorbed on soil surfaces. The differences in aggregate could be as a result of tillage operations as conventional tillage breaks down large aggregates into smaller aggregates. This was in agreement with Zheng *et al*. (2018) where intensive tillage broke down soil particles into smaller particles, which ultimately influenced the soil structure and aggregate stability. According to Han and Zhang (2019), larger aggregates were more sensitive to management practices than smaller aggregates. However, soil structure can be improved by adopting conservation tillage, enhancing aggregation due to increased organic matter content binding small aggregates to larger aggregates. Larger aggregates increase SOC stocks as they enhance carbon build-up within soil particles (Li *et al*., 2016).

4.5.3 Correlation Analysis

Correlation among SOC stocks and other soil properties for Shikomoli

Significant positive correlation of clay with SOC stocks at all sampled depths implied that as clay content increased the SOC stocks increased since clay particles tend to protect SOC from decomposition hence high SOC stocks.

This was in agreement with Azlan *et al*. (2012) and Adhikari and Bhattacharyya, (2015) where clay and SOC stocks was found to have positive correlation and was attributed to high clay content soils. Significant positive correlation of manganese with SOC stocks at all sampled depths means that increase in manganese content increases the SOC stocks as manganese promotes decomposition of the recalcitrant organic matter. Piikki *et al*. 2019 also found a positive correlation between manganese and SOC which was attributed to increased mineralization of the organic matter. Significant positive correlation of CEC with SOC stocks observed at the subsurface layer (20-40 cm) implies that as CEC increased the SOC stocks increased because high CEC indicates a high surface charge for organic matter adsorption. The results was supported by a study by Waswa *et al*. (2013) where SOC stocks and CEC showed positive correlation due to high organic matter content. Significant negative correlation of sand with SOC stocks found at all sampled depths implies that increase in sand content reduces the SOC stocks due to accelerated decomposition. High sand content have large particles increasing the surface area exposed to decomposition thus lowering the SOC stocks. Powers and Schlesinger, 2002 also reported negative correlation of sand content and SOC stocks. Significant negative correlation of bulk density with SOC stocks observed at subsurface layer (40-60 cm) implies that increase in bulk density lowers the SOC stocks because increased bulk density means the soil is more compacted reduced the storage of SOC stocks. This was in agreement with a study Saiz *et al*. (2012) where bulk density and SOC had negative correlation.

Correlation between soil carbon stocks and other soil properties for Mukuyu

Significant negative correlation of sand with SOC stocks observed at the surface layer (0-20 cm) means that high sand content reduces SOC stocks through the accelerated mineralization of organic matter. The residues are mostly applied on the upper layers and this explains the negative association. Further high sand levels lowers biomass production as a result of leaching, reduced moisture and nutrients. This was in line with Muktar *et al*. (2018) where a negative correlation between sand and SOC stocks were also reported and was attributed to high decomposition rate. Significant positive correlation of silt with SOC stocks found at surface layer (0-20 cm) means that higher silt content promotes the storage of carbon thus increased carbon stocks. Silt has small particles thus protect SOC from decomposition. Further, silt have a high adsorptive capacity increasing the SOC stocks.

This was similar to the finding of Were *et al*. (2016) where positive correlation between silt and SOC stocks and was due to reduced decomposition rate. The significant positive correlation of CEC with SOC stocks at surface (0-20 cm) and sub-surface (20-40 cm) implies that as CEC increased the SOC stocks increased due to high carbon adsorbed into the soil surfaces. A similar finding was found by Odour *et al*. (2018); Orgill *et al*. (2017) and Srinivasaro *et al*. (2009) where positive correlation CEC and SOC stocks was also reported and was attributed to larger specific surface area hence more storage of SOC stocks. The significant positive correlation of manganese with soil carbon stocks at 0-20 cm and 20-40 cm depth implies that higher manganese content increased SOC stocks because of decomposition of recalcitrant organic matter thus releasing more carbon content into the soils. Stendahl *et al*. (2017) reported contradicted findings where high manganese content reduced SOC stocks but was explained by the different land uses.

4.6 Conclusion and Recommendations

The study was conducted to evaluate the variability of SOC according to depth and physicochemical properties in smallholder farming systems in western Kenya. In both sites, SOC was found to be deficient. Further total nitrogen, available phosphorus, CEC and copper were deficient. Clay, CEC, and manganese had a positive correlation, while clay and bulk density had a negative correlation with SOC stocks. There was a negative correlation between sand and a positive correlation between silt, CEC and manganese in Mukuyu. In Shikomoli, there was a significant relationship between these parameters that govern the fertility of the soils hence the deficiency limits crop productivity and biomass production. In Shikomoli, positive correlation between SOC stocks micro-aggregate, silt, clay, geometric mean diameter and mean weight diameter while in Mukuyu significant relationship between large macro-aggregate, mean weight diameter, geometric mean diameter and micro-aggregates with SOC stocks was observed. To enhance SOC stocks among smallholder farmers, management practices that increase nitrogen content, available phosphorus, cation exchange capacity, geometric mean diameter and mean weight diameter for the stability of soil aggregates is recommended. The recommendation of this study is the need to identify management practices that improve the physical and chemical properties at lower depths.

CHAPTER FIVE: USING THE CROPSYST MODEL TO SIMULATE SOIL ORGANIC CARBON DYNAMICS UNDER DIFFERENT MANAGEMENT PRACTICES IN VIHIGA AND KAKAMEGA COUNTIES, WESTERN KENYA

5.1 Abstract

Conventional farmer management practices (here referred to as, business-as-usual scenario) have been a major contributor to decreasing carbon content in the soils. However, this can be reversed by the adoption of improved practices such as conservation agriculture, which has been reported to increase soil carbon stocks. The objectives of this study was to (i) calibrate and validate the CropSyst model using data from farm' fields in Western Kenya and to (ii) assess soil organic carbon (SOC) sequestration under business-as-usual compared to conservation agriculture (zero tillage and full residue retention). Six farms under maize cropping systems were identified with contrasting soil texture and management practices representing the two sites. The model was calibrated using average farmer reported yields and measured SOC. The calibrated model was then used to project long-term (50 years) SOC trends assuming farm would continue to practice business-as-usual or, alternatively, conservation agriculture. After calibration, CropSyst reproduced observed grain yields and SOC stocks with an Root Mean Square Error (RMSE) of 2.66 Mg/ha and 0.54 Mg/ha, and a Pearson Coefficient of 0.99 and 0.94, respectively. Under the conventional farmer management practices, SOC stocks decreased for all the farms while under conservation agriculture, SOC stocks increased. Differences in simulated SOC stocks and grain yield could be contributed by climatic conditions (temperature and precipitation), soil texture (clay, sand and silt), nutrient deficiency, initial carbon content, crop water stress, nitrogen stress and biomass yields. The average annual loss of SOC stocks in the upper 20 cm for business-as-usual scenario ranged from 0.03 to 0.19 t C/ha/yr. while in conservation agriculture, SOC stocks increased annually to up to 0.28 t C/ha/yr. Thus, a moderate carbon sequestration over the next 50 years could be obtained by the adoption of conservation agriculture. The moderate carbon sequestration rate could be further increased by coupling crop rotation, intercropping and manure application.

Keywords: CropSyst model, Business-as-usual scenario, Conservation agriculture, Soil carbon stocks

5.2 Introduction

Sufficient amounts of organic matter in soils (SOM) is essential in tropical croplands governing the provision of ecosystem services and influencing the chemical, biological, and physical properties of soils and consequently crop productivity (Valdez *et al*., 2017; Fontana *et al*., 2015; Rutkowska and Pikuła, 2013; Wang *et al*., 2009). SOM improves nutrient retention and uptake efficiency, soil aeration, the buffer capacity of the soil, microbial population and soil aggregate stability (Lal, 2016; Kane, 2015; Nyberg *et al*., 2012). Carbon is the major building block of SOM. Soil organic carbon (SOC) can be increased through improved management practices such as conservation agriculture (Steward *et al*., 2018). Biophysical factors, which include land management activities, climate and soil type strongly interact and influence SOC concentration (Sommer *et al*., 2018; Azlan *et al*., 2012; Nyberg *et al*., 2012; Batjes, 2010). A loss of SOM is a widespread consequence of soil degradation in Sub-Saharan Africa. Degradation is often caused by unsustainable agricultural intensification practices, (physical) soil erosion and low organic matter and nutrient inputs (Tully *et al*., 2015). In Sub-Saharan Africa, this has led vast lands and soils with a scarcity of nutrients, poor aggregate stability, low cation exchange capacity and ultimately reduced yields (FAO and ITPS, 2015; Ren *et al*., 2014; Moebius-Clune *et al*., 2011).

SOC has been on the decline in smallholder systems due to inappropriate agricultural management practices (Musinguzi *et al*., 2013). Sommer *et al*. (2018) reported soil carbon losses of 50 -70% in western Kenya due to unsuitable practices such as continuous tillage, intensified crop production without replenishing the soil with inputs resources. Further, Waswa (2012), reported low SOC contents in smallholder farms in western Kenya that was way below a threshold value, which Waswa set to 2%, making the systems more susceptible to soil degradation.

The opposite of losses of SOC, i.e., carbon sequestration, is where carbon is absorbed from the atmosphere and stored in the soil. It is a crucial process in mitigating the impact of climate change, improving soil fertility, and controlling soil erosion (FAO, 2017). SOC sequestration is possible by adopting judicial agricultural management practices, such conservation agriculture (Singh *et al*., 2018; Sombrero and Benito, 2010). Conservation agriculture refers to agricultural systems where there is mulching using crop residue, minimum soil disturbance, cover cropping, a diverse wide crop rotation and integrated nutrient management (Lal, 2017).

Conservation agriculture was reported to increase SOC stocks between 0.28 and 0.96 Mg/ha in Sub-Saharan Africa for a period of 2 to 16 years in a meta-analysis study by Powlson *et al*., 2016. Much has been done on the evaluation of the management practices on SOC dynamics but, they do not take into consideration projections of future SOC levels and identification of the best practices that restore, retain or increase SOC in the short-term to medium-term basis *(*Jackson *et al*., 2017; Don *et al*., 2015; Gnanavelrajah *et al*., 2008). Therefore, it is necessary to predict the potential SOC stocks under various management practices with due consideration of the biophysical conditions that drive such processes.

SOC stocks have been estimated using various approaches including field experiments and modeling. Field experiments are resource-demanding and time-consuming. In that regard, computer-based modeling is a promising – fast and comparably cheap – tool for assessing carbon stocks and development of management practices that have the potential for carbon sequestration, maintaining soil fertility and improving crop yields (Musinguzi *et al*., 2014). Further, models have been used over decades to depict field experiments and project future SOC stocks under different management practices (Wan *et al*., 2011). These include: CropSyst (Stöckle *et al*., 2003), RothC (Coleman and Jenkinson, 2005), CENTURY (Parton, 1996), DSSAT (Jones *et al*., 2003) and APSIM (…), among other, less-known models. These models preferably ought to be coupled with field experiments for calibration and prediction of SOC stocks responses to management, soil, and climate. A further thorough evaluation is required before they are used in making projections.

We used the crop-soil simulation model CropSyst, as this has been widely applied to simulate carbon dynamics and yields in different regions, including tropical regions and Kenya in particular (Sommer, 2017; Stöckle, 2012). The study's goals was to (i) calibrate and validate CropSyst for Western Kenya and (ii) assess SOC dynamics under business-as-usual scenario (existing farm practices) and compare this to a scenario where conservation agriculture (minimum tillage and full residue retention) was practiced.

5.3 Materials and Methods

5.3.1 Description of the study site

The study was carried out in Mukuyu and Shikomoli villages in western Kenya as described in chapter three section 3.3.2.

5.3.2 Climatic, soil and management data

Daily rainfall amounts and minimum and maximum temperature for the two sites were available from the Kenya Meteorological Department for the year 1984-2018. However, the CropSyst model requires climatic data that, besides daily rainfall and maximum and minimum temperature, include solar radiation, relative humidity, and wind speed. Thus, satellite-derived data were downloaded for Mukuyu and Shikomoli from the NASA-POWER Agro-climatology database (https://power.larc.nasa.gov/data-access-viewer/) for a period of 35 years from 1984 to 2018 to complete station data. NASA daily data for solar radiation, relative humidity, minimum and maximum temperature, rainfall, wind speed at 10 m were available at a resolution of 0.5° x 0.5°. Further, maximum and minimum humidity was calculated from the average relative humidity. For accuracy of satellite data, bias correction using the procedure described by Sommer (2011-unpublished) was done to correct the bias between observed and satellite data for temperature and precipitation. However, bias correction was not done on other variables, i.e. solar radiation, wind speed, as (a) such bias is usually very small, (b) no own data were available to carry out such correction.

Six farms representing the two sites with different management practices and contrasting soil textures were selected (Table 5.1, Table 5.2). More detailed measured soil properties is indicated in appendix 5. In addition, the adoption of conservation agriculture management practice are presented in (Table 5.3).

Table 16. Farms’ management under business-as-usual management (current management practices)

Farm	Site	Mineral fertilizer application (kg N/ha)	Type of mineral fertilizer	Manure application (t/ha)	Proportion of crop residue retained (%)	Lat	Long
Farm 1	Shikomoli	9	DAP, CAN	0.4	5	0^0 03' 07" N	34^0 47' 02" E
Farm 2	Shikomoli	13	CAN	1	20	0^0 03' 14" N	34^0 47' 00" E
Farm 3	Mukuyu	36	DAP, CAN, Urea	-	5	0^0 44' 16" N	34^0 55' 91" E
Farm 4	Mukuyu	38	DAP, CAN	-	10	0^0 44' 07" N	34^0 56' 42" E
Farm 5	Mukuyu	72	CAN, NPK	-	70	0^0 44' 35" N	34^0 56' 30" E
Farm 6	Mukuyu	26	CAN, Mavuno	-	20	0^0 43' 83" N	34^0 56' 78" E

DAP-Diammonium phosphate; CAN-Calcium ammonium nitrate; NPK- Nitrogen phosphorus and potassium

Table 17. Measured soil properties for all the farms

Farm	**Depth**	**TN**	**TC**	**CN ratio**	**SOC**	**P^H**	**clay**	**Sand**	**Silt**	**BD**	**Avail. P**	**CEC**
	cm	**%**	**%**		**Mg/ha**		**%**	**%**	**%**	**g/cm^3**	**ppm**	**cmol/kg**
Farm 1	0-20	0.04	0.46	10.60	15.00	6.44	12.14	77.88	9.98	1.64	35.18	6.12
Farm 1	20-40	0.037	0.37	9.97	11.33	6.14	12.15	77.85	10.00	1.54	20.38	6.48
Farm 1	40-60	0.039	0.36	9.33	13.00	6.14	16.15	73.86	10.00	1.79	31.83	6.08
Farm 2	0-20	0.079	0.79	10.03	22.22	5.60	24.13	69.88	5.99	1.40	37.55	6.20
Farm 2	20-40	0.069	0.66	9.56	20.81	5.40	28.12	63.90	7.99	1.57	34.34	4.40
Farm 2	40-60	0.068	0.67	9.84	21.98	5.27	28.15	63.85	8.00	1.64	30.29	6.80
Farm 3	0-20	0.097	1.17	12.06	32.40	5.52	24.88	57.49	17.64	1.38	31.41	7.44
Farm 3	20-40	0.079	0.93	11.80	27.26	5.76	26.87	55.50	17.63	1.46	23.45	7.08
Farm 3	40-60	0.06	0.73	12.18	21.12	6.01	32.86	51.51	15.63	1.44	16.05	11.60
Farm 4	0-20	0.091	1.14	12.47	30.26	5.66	37.20	54.81	7.99	1.33	20.24	9.20
Farm 4	20-40	0.077	1.03	13.36	33.96	5.28	43.20	48.81	7.99	1.65	25.27	5.40
Farm 4	40-60	0.076	1.02	13.36	32.52	5.28	45.60	48.4	6.00	1.60	5.30	8.60
Farm 5	0-20	0.207	2.75	13.29	58.50	5.98	35.60	34.76	29.64	1.06	20.10	22.60
Farm 5	20-40	0.124	1.76	14.17	47.61	6.10	39.58	38.78	21.63	1.35	28.06	25.20
Farm 5	40-60	0.083	1.20	14.40	32.69	6.24	37.60	42.76	19.64	1.37	18.70	19.00
Farm 6	0-20	0.111	1.50	13.52	42.70	5.52	39.54	52.83	7.63	1.42	38.53	9.90
Farm 6	20-40	0.09	1.27	14.11	38.70	5.33	49.57	46.79	3.64	1.52	5.72	7.60
Farm 6	40-60	0.088	1.20	13.67	34.54	5.42	55.58	40.78	3.64	1.44	8.93	10.00

TN- total nitrogen, TC-total carbon, CN- carbon to nitrogen, BD-bulk density, Avail. P-available phosphorus, CEC-cation exchange capacity

Table 18. Farms’ management under conservation agriculture

Farm	Mineral fertilizer application (kg N/ha)	Type of mineral fertilizer	Manure application (t/ha)	Proportion of crop residue retained (%)	Proportion of crop residue retained (%)	Tillage operation	Lat	Long
Farm 1	9	DAP, CAN	0.4	100	50	Minimum tillage	0^0 03' 07" N	34^0 47' 02" E
Farm 2	13	CAN	1	100	50	Minimum tillage	0^0 03' 14" N	34^0 47' 00" E
Farm 3	36	DAP, CAN, Urea	-	100	50	Minimum tillage	0^0 44' 16' 'N	34^0 55' 91" E
Farm 4	38	DAP, CAN	-	100	50	Minimum tillage	0^0 44' 07" N	34^0 56' 42" E
Farm 5	72	CAN, NPK	-	100	50	Minimum tillage	0^0 44' 35" N	34^0 56' 30" E
Farm 6	26	CAN, Mavuno	-	100	50	Minimum tillage	0^0 43' 83" N	34^0 56' 78" E

DAP-Diammonium phosphate; CAN-Calcium ammonium nitrate; NPK- Nitrogen phosphorus and potassium

Soil sample for the six farms studies were taken at three depths: 0-20, 20-40 and 40-60 cm. For determination of soil bulk density, cylindrical steel rings (100 cm^3) were used, and undisturbed sample at each depth from the centre of the plot taken. The collected samples were air-dried, ground and sieved using a 2 mm sieve. Bulk density was determined by oven drying at 105 °C for 48 hours to a constant weight (Blake, 1965). Analysis of soil texture was done using the Bouyoucos hydrometer method by dispersing the soil with sodium hexa-metaphosphate (Day, 1956). Soil pH (H_20) was measured in a 1:2 soil: water suspension with a glass electrode. Cation exchange capacity was determined using the Metson (1961) method. A C/N elemental analyzer (Macro Cube, Elementar GmbH, Germany) was used to determine the total carbon, which was then converted to percent SOM using a standard conversion factor of 1.724 (assuming SOM contains 58% SOC), and assuming that these tropical soils do not contain inorganic carbon in the form of calcium-carbonate.

Management data for the entire cropping season, i.e. planting date, crop residue retention, tillage operation, harvest and inputs used, was obtained by administering standard questionnaire through an interview (Appendix 1).

5.3.3 CropSyst model

CropSyst version 4.06.08 was applied to simulate crop growth and SOC dynamics under the business-as-usual and conservation agriculture scenarios. CropSyst is a daily time step cropping systems simulation model developed to serve as an analytical tool for researching the effects of climate, soils, and management on cropping systems productivity and the environment. It simulates the dynamics of soil organic matter, soil-water budget, soil-plant nitrogen budget, crop phenology, canopy and root growth, biomass production, crop yield, residue production and decomposition, as well as – if enabled – soil erosion by water and salinity. Weather, soil characteristics, crop characteristics, and cropping system management, including tillage operations, nitrogen fertilization, and residue management, all influence these processes (Stöckle *et al*., 2003).

CropSyst uses a multi-pool approach to represent soil organic matter decomposition, analogous to the well-known CENTURY model (or its daily-time step version DAYCENT). Pools are Microbial Biomass (MB), Metastable Active (MA), Labile Active (LA) and Passive organic matter. Decomposition is based on first-order kinetics (Stöckle *et al*., 2010), which is represented by decomposition constants varying for each pool (Table 5.4).

Table 19. CropSyst soil organic matter pools, decomposition rate constants (k) and standard carbon to nitrogen ratio

SOM pool	**k (day^{-1})**	**CN ratio**
Microbial biomass	0.00499	8
Labile active	0.01999	25
Metastable active	0.00050	15
Passive	0.0000185	11

In addition, decomposition of MB is affected by silt and clay contents, MB residue transferred to MA and LA is linked to soil layers that have recently been disturbed by tillage. During decomposition, a significant fraction of the carbon is lost as CO_2 from the decomposition of the various pools due to specific constants, with the remainder being transferred to other pools. The model calculates how much carbon is allocated to each pool from the initial SOM (Rinaldi *et al*., 2017). Therefore, the model requires each separate pool for each layer to be initialized.

Each separate pool was achieved by running the model for a duration of 3090 years under forest, followed by 10 years of subsistence maize with low manure inputs using DAYCENT model (Del Grosso *et al*., 2002). The spin-up phase for the 4 SOM pools (figure 5.2) and figure 5.3 shows the total SOC for all the farms. The final carbon distribution in the various pools after 3090 years of equilibrium was used as the starting point for all subsequent simulations. In the soil profile description, real, observed SOM contents were used as initial soil values.

Saturated hydraulic conductivity, air entry potential, and volumetric water content at field capacity and wilting point were derived using soil texture and bulk density and CropSyst's intrinsic pedo-transfer model. Runoff was simulated using the United States Department of Agriculture (USDA) curve number model. Evapotranspiration was estimated using the Penman-Monteith method.

Figure 4. SOM pools (microbial biomass, active labile, active metastable and passive) for all the farms

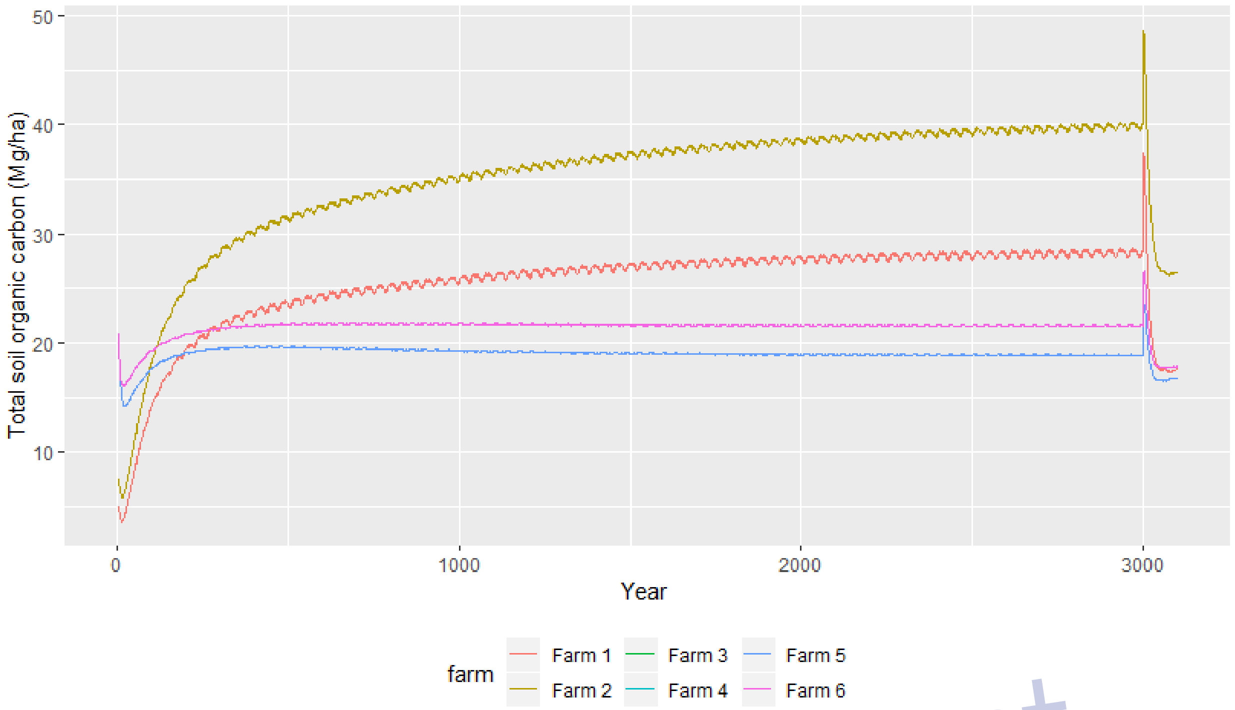

Figure 5. Total SOC for all the farms

5.3.4 Model simulations

The input data required for simulation include observed weather data, details of the various management activities (time and method of fertilization, date of planting, harvest, tillage and residue management), soil and crop data. Initial percent distribution, and observed total, of SOM pool was used to simulate maize growth based on the documented general management (Table 5.1) for the year 2018. Simulated maize yields were calibrated using observed average yields for all the farms. Maize crop physiological parameters (Table 5.5) were either adjusted from literature review and also trial for best fit or default values used to match the simulated with reported yields.

Table 20. CropSyst crop model parameters for maize

Parameters	**Default value**	**Value used in this study**
Base temperature (^{0}C)	3	8
Cutoff temperature (^{0}C)	22	34
Canopy extinction coefficient for total (global) solar radiation	0.50	0.50
Evapotranspiration crop coefficient at full canopy	1	1

Parameters	**Default value**	**Value used in this study**
Leaf water potential at the onset of stomatal closure (J/kg)	-700	-1200
Wilting leaf water potential (J/kg)	-1600	-1800
Maximum water uptake (mm/day)	10	14
Transpiration use efficiency when VPD is at 1kPa (g BM/kg H_2O)	5	5.2
Scaling coefficient of TUE regression	0.45	0.45
Radiation use efficiency total radiation basis (g/MJ)	4	4
Leaf water potential that begins reduction of canopy expansion (J/kg)	-800	-700
Leaf water potential that stops canopy expansion (J/kg)	-1200	-1100
Initial green leaf area index (m^2/m^2)	0.011	0.08
Min. green leaf area (m^2/m^2)	0.011	0.011
Maximum expected leaf area (m^2/m^2)	5	7
Specific leaf area at optimum temperature (m^2/kg)	22	20
Fraction of max. LAI at physiological maturity	0.8	0.8
Stem/leaf partition coefficient	3	2.5
Leaf area duration (degree days)	800	700
Leaf area duration sensitivity to water stress	1	1
Thermal time to reach emergence (^{0}C-days)	100	140
Thermal time to reach maximum root depth (^{0}C-days)	1040	1000
Thermal time to reach end canopy growth (^{0}C-days)	1040	900
Thermal time to begin flowering (^{0}C-days)	1000	980
Thermal time to begin filling (^{0}C-days)	1020	1230
Begin senescence (^{0}C-days)	1080	1400
Full senescence (^{0}C-days)	1501	1680
Physiological maturity (^{0}C-days)	1500	1770
Adjustment factor for phenologic response to stress (^{0}C-days)	1	1
Biomass translocation to grain fraction	0.4	0.
Maximum root depth (m)	1.5	1

The calibrated model was then validated by the observed SOC stocks.The calibrated model was then used to project long-term (50 years) SOC trends of the farms under conventional management practices (here referred to as, business-as-usual-scenario).

In addition, 50 years SOC dynamics where simulated, assuming farm had adopted conservation agriculture (i.e. full residue retention and minimum tillage).

ClimGen 4.6.08, a weather generator part of CropSyst (Stöckle *et al*., 1999), was used to generate 50 years (2019-2068) of climate for running the future projections.

5.3.5 Data analyses

Statistical model evaluation was performed using the root mean square error (RMSE; Eq. 1), the relative root mean square error (RRMSE, Eq. 2) and the Pearson coefficient (R) to determine the fit between the simulated and average reported farm yields. All the analysis was done using the R software 3.5.1 (R Core Team, 2018).

$$RMSE = \frac{\sqrt{\sum_{i=1}^{n}(observed_i - simulated_i)^2}}{n} \qquad \text{Equation 1}$$

$$RRMSE = \frac{RMSE}{Avg(observed)} *100 \qquad \text{Equation 2}$$

5.4 Results

5.4.1 Model performance

The average observed and simulated SOC stock was 33.51 and 31.24 Mg C/ha, respectively while the average observed and simulated maize yields were 1.13 and 1.55 t/ha, respectively (table 5.6). The RMSE was 2.66 and 0.54 for yields and carbon stocks, respectively, while the RRMSE was 7.9 and 47.36 for yields and carbon stocks, respectively (table 5.6). For the SOC stocks, the coefficient value was 0.99 and for the grain yields, the value was 0.94 (table 5.6).

Table 21. Statistical comparison of observed and simulated grain yield and soil carbon stocks (0-20 cm depth) for all the farms

		SOC stocks (Mg C/ha)		Grain yield (t/ha)	
Farm	**Site**	**observed**	**simulated**	**observed**	**simulated**
Farm 1	Shikomoli	15.00	13.72	0.45	0.59
Farm 2	Shikomoli	22.22	21.90	0.63	0.88
Farm 3	Mukuyu	32.40	28.81	0.68	1.37
Farm4	Mukuyu	30.26	27.51	0.56	1.58
Farm 5	Mukuyu	58.50	57.07	3.15	3.50
Farm 6	Mukuyu	42.70	38.43	1.32	1.37
Average		33.51	31.24	1.13	1.55
RMSE		2.66		0.54	
RRMSE		7.9%		47.36%	
Pearson coefficient		0.99		0.94	

5.4.2 Long-term prediction of average SOC stocks, biomass and grain yield under business-as-usual and conservation agriculture

Over the predicted years (50 years), SOC stocks were predicted to decline for all the farms under business-as-usual management practice but at different rates except for farm 2, which was stable. (Figure 5.4). The model projected an increase in SOC stocks for all the farms under conservation agriculture but declined business-as-usual management (figure 5.4). Farm 1 to 6 represents farmers selected. Biomass yield under conservation agriculture and grain yield under business-as-usual and conservation agriculture management were predicted to fluctuate over the years (figure 5.5, figure 5.6).

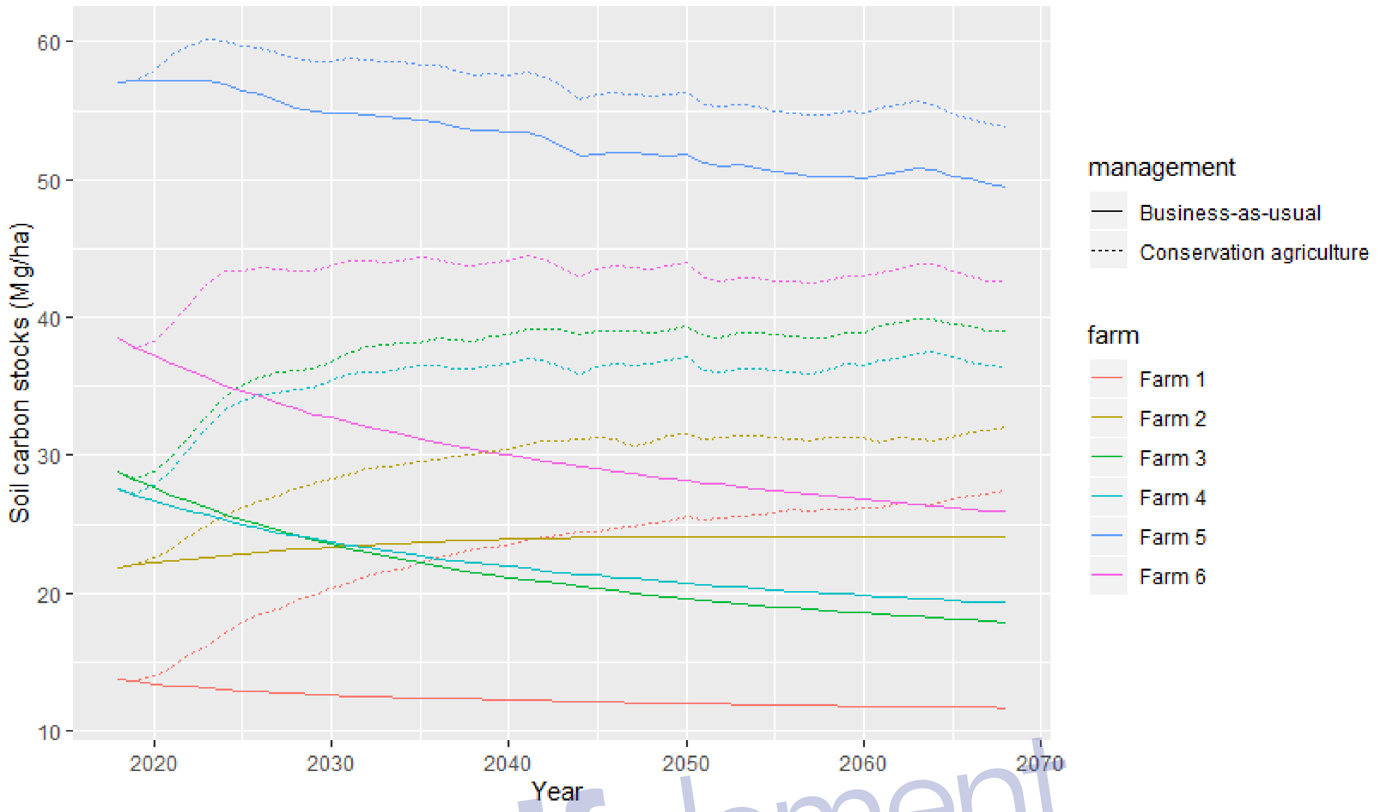

Figure 6. Predicted SOC stocks for all farms for 50 years under business-as-usual and conservation agriculture

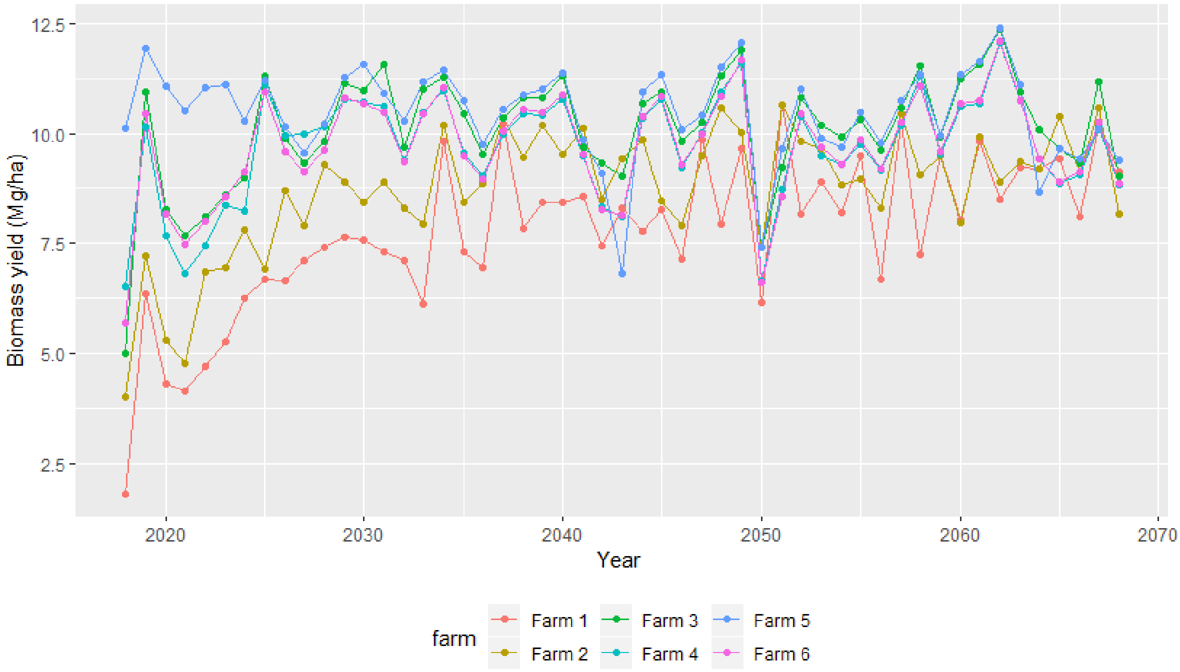

Figure 7. Predicted average above ground biomass for all farms for 50 years under conservation agriculture

Figure 8. Predicted average yields for all farms for 50 years under business-as-usual and conservation agriculture

5.4.3 Long-term prediction of average nitrogen and crop water stress under business-as-usual and conservation agriculture

The model predicted that under business-as-usual and conservation agriculture, both systems experienced crop water stress more in comparison with nitrogen stress (figure 5.7). Under business-as-usual, nitrogen stress would not be experienced while under conservation agriculture, there would be nitrogen stress only in the earlier years.

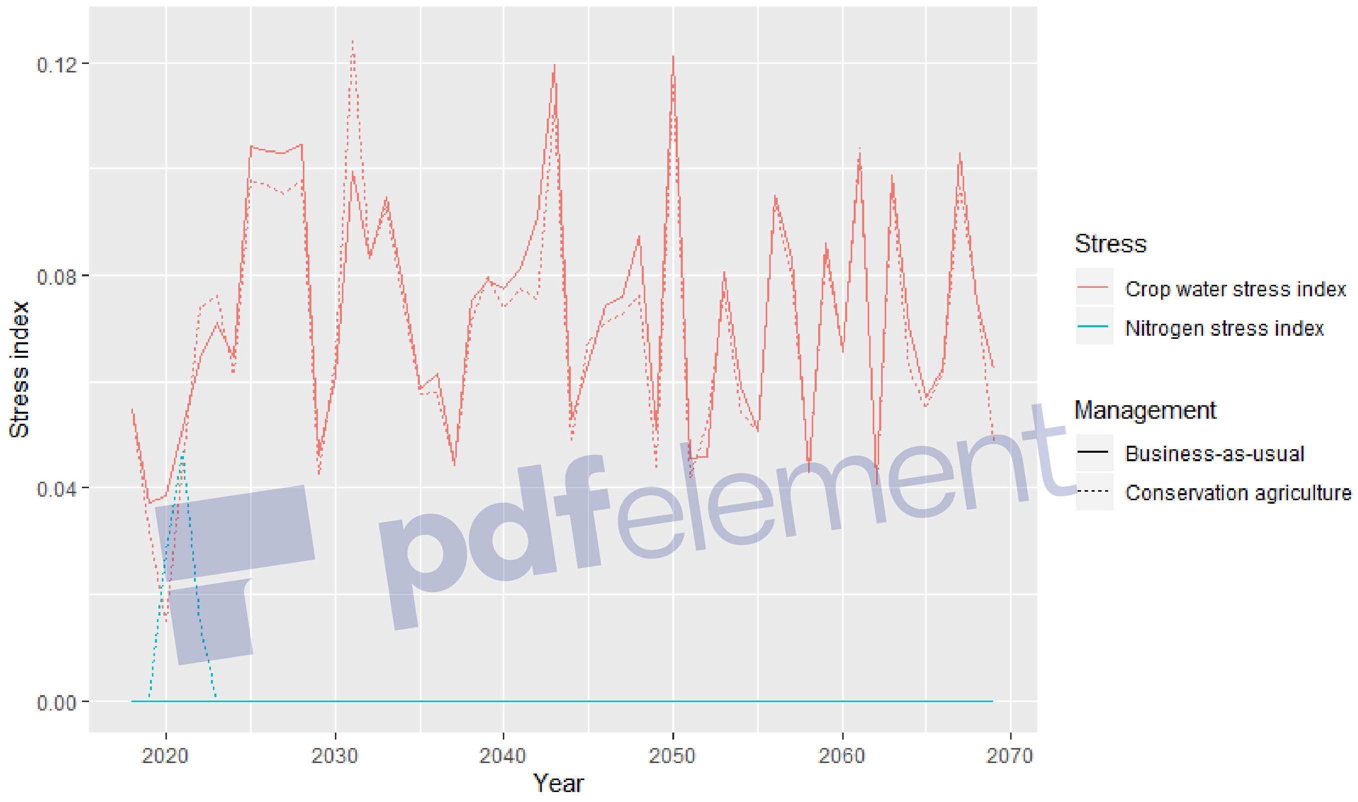

Figure 9. Predicted average nitrogen and crop water stress index under business-as-usual and conservation agriculture for farm 5

5.4.4 Predicted SOC stocks range for all the farms

The highest predicted SOC stock was 60.15 Mg/ha for farmer 5 under conservation agriculture at 0-20 cm depth, while the lowest being 8.34 Mg/ha for farmer 1 under business-as-usual at 20-40 cm depth (Table 5.7*)*.

Table 20. SOC stocks ranges for all the farms

	Management			**Management**		
	Business-as-usual			**Conservation agriculture**		
	Depth (cm)			**Depth (cm)**		
Farm	**0-20**	**20-40**	**40-60**	**0-20**	**20-40**	**40-60**
Farm 1	11.69-13.73	8.34-10.82	11.59-12.85	13.63-27.38	10.76-14.62	12.84-17.59
Farm 2	22.04-24.08	18.97-20.11	21.89-22.33	22.05-32.00	20.14-22.36	21.90-25.94
Farm 3	17.90-28.19	20.79-26.13	20.60-21.32	28.28-39.90	26.13-26.84	21.32-25.73
Farm 4	19.29-27.10	27.14-32.63	31.40-32.46	27.17-37.53	31.33-32.65	32.47-34.71
Farm 5	49.53-57.25	40.02-46.05	33.59-35.17	53.84-60.15	40.67-45.96	34.00-35.72
Farm 6	25.92-37.73	29.86-36.76	32.67-34.22	37.78-44.44	35.63-36.76	34.22-35.86

5.4.5 Average annual changes of SOC stocks per hectare per year

Predicted average annual losses and gains of SOC stocks under different management practices indicate that, under the business-as-usual management, the highest loss (0.24 Mg C/ha/yr) would be from farm 6 at 0-20 cm depth (table 5.8) with the highest gain (0.04 Mg C/ha/yr) from farm 2 at 0-20 cm depth and farm 5 at 40-60 cm depth (Table 5.8). In addition, under conservation agriculture, the highest loss (0.11 Mg C/ha/yr) would be from farm 5 at 20-40 cm depth with the highest gain (0.28 Mg C/ha/yr) from farm 1 at 0-20 cm depth (Table 5.8). Further, for all the farms under business-as-usual management SOC stocks were predicted to be lost at all depths except for farm 2 at 0-20 cm and 40-60 cm depth and farm 5 at 40-60 cm depth. Under conservation agriculture, SOC stocks were predicted to be gained at all depths except for farm 4 at 20-40 cm depth, farm 5 at 0-20 cm and 20-40 cm depth and farm 6 at 20-40 cm depth (Table 5.8).

Table 21. Predicted average annual losses and gains of SOC stocks under business-as-usual scenario and if conservation agriculture was adopted

Average annual loss/gain of SOC stocks (Mg C/ha/yr)							
		Management practice					
		Business-as-usual			Conservation agriculture		
Farm	Depth (cm)	Losses	Gains	Standard deviation	Losses	Gains	Standard deviation
Farm 1	0-20	0.04		1.34		0.28	9.73
	20-40	0.05		1.70		0.08	2.73
	40-60	0.03		0.89		0.09	3.36
Farm 2	0-20		0.04	1.42		0.20	7.03
	20-40	0.03		1.08		0.04	1.58
	40-60		0.01	0.35		0.08	2.86
Farm 3	0-20	0.21		7.28		0.22	7.64
	20-40	0.11		3.78		0.01	0.38
	40-60	0.01		0.51		0.09	3.25
Farm 4	0-20	0.16		5.52		0.19	6.54
	20-40	0.11		3.88	0.03		1.14
	40-60	0.02		0.75		0.04	1.55
Farm 5	0-20	0.15		5.38	0.07		2.33
	20-40	0.13		4.43	0.11		3.97
	40-60		0.04	1.38		0.05	1.77
Farm 6	0-20	0.24		8.35		0.10	3.44
	20-40	0.14		4.88	0.05		1.88
	40-60	0.03		1.10		0.04	1.40

5.5 Discussion

5.5.1 Model performance

The model simulated SOC stocks quite reasonably well, which was shown by the Pearson coefficient and RRMSE value. The Pearson coefficient was close to 1, which showed close relationship between the simulated and observed values. The RRMSE value was less than 10%, which means the model simulated the SOC stocks excellently thus a good match between the recorded and model output values.

However, the model overestimated the grain yields with a RRMSE value of more than 40%, which showed poor prediction by the model. The model has no inbuilt mechanism for phosphate as input thus failure of the model to incorporate phosphorus deficiency when simulating the yields. Hence an overestimation of the yields as majority of the farms were phosphorus-deficient at all sampled depths. Phosphorus is the most important essential nutrient for maize production and governing crop yields (Dhillon *et al*., 2017). Hence, phosphorus deficiency in soils negatively affects the yields by inhibiting energy utilization, delaying maturity, and stunting growth (Wasonga *et al*., 2010). Further, the CropSyst model does not consider pest and weed infestation thus, this maybe another of the possible reasons for the overestimation of grain yields. The differences in the simulated and observed yield results could also be as a result of the interaction between climate, soil type and input levels (Soler *et al*., 2011). The nutrients were low thus low soil fertility below the recommended level thus negative impact on the yields. Munialo *et al*., 2019 reported that maize yields are affected more by soil factors compared to management.

5.5.2 Long-term prediction of average SOC stocks, biomass and grain yield under business-as-usual and conservation agriculture

Over the predicted years (50 years), SOC stocks were predicted to decline for all the farms under business-as-usual management practice. The SOC stocks decline could be attributed to low inputs and tillage operations.

Low inputs in terms of crop residue and fertilizer contribute to decreasing SOC stocks since limited crop residue application reduces organic matter added into the soil while inadequate fertilizer lower biomass production and consequently carbon input. In addition, tillage operations that is convention tillage in this case destroy soil aggregation exposing organic matter and ultimately accelerate decomposition. This is in line with research done by Berazneva *et al*. (2014) and Musinguzi *et al*. (2013), illustrating continuous cropping with minimal additions of inputs depletes the carbon pool thus decline in the carbon content because organic matter additions into the soil are inadequate to replenish the lost SOC stocks.

The model projected an increase in SOC stocks for all the farms under conservation agriculture compared to business-as-usual. This is attributed to minimal tillage and crop residue retention. Minimum tillage improves soil health by enhancing the overall soil structure in terms of physical, chemical, and biological properties.

Retention of crop residues increase the organic matter added which translates to increased SOC stocks. This is in line with a study done by Sommer *et al*. (2018) in western Kenya, which found that limited tillage and crop residue application decreased SOC losses. Further, Sombrero and Benito, (2010) reported similar findings where SOC stocks increased after the adoption of minimum tillage and crop residue retention. However, the SOC stocks fluctuated and this can be explained by an increase and decrease of biomass yield thus causing inconsistencies over the years. In addition, the study did not incorporate intercropping or cove cropping thus lower biomass produced and returned to the soil.

Grain yield was predicted to fluctuate over the years under both business-as-usual and conservation agriculture management. Due to decline in SOC stocks and low inputs, the decline in soil fertility resulted in decreased grain yield under business-as-usual management. A research by Blecourt *et al*. (2019) found that a decrease in SOC stocks, combined with nutrient deficiency, resulted in lower maize yields which was consistent to our results. Under conservation agriculture management, the variation of grain yield may be due to the change of SOC stocks and crop water stress. However, a research by Odhiambo *et al*. (2015) in western Kenya obtained contradictory results and this was explained by the incorporation of integrated management practice and herbicide application. Although, business-as-usual compared to conservation agriculture management, the latter had higher yields due to higher carbon stocks.

These results were similar to a study conducted by Thierfelder *et al*. (2013) where minimum tillage coupled with crop residue was reported to have higher yields compared to conventional tillage.

5.5.3 Long-term prediction of average nitrogen and crop water stress under business-as-usual and conservation agriculture

The model predicted that under business-as-usual and conservation agriculture, both systems would experience crop water stress more in comparison with nitrogen stress. Under business-as-usual, nitrogen stress would not be experienced, while under conservation agriculture, there would be nitrogen stress only in the earlier years. Nitrogen and crop water stress index range from 0 to 1, with 0 denoting no stress and 1 is maximum stress. Nitrogen stress earlier in the years under conservation agriculture could be due to nitrogen immobilization as result of retention of crop residues. Crop residues tend to immobilize applied nitrogen from chemical fertilizer. Crop water stress could be resulting from issues of climate change resulting to low rainfall.

Grain filling and flowering are majorly affected by water stress and consequently negative impact on grain yield and biomass productivity (Stöckle *et al*., 2003).

5.5.4 Predicted SOC stocks range for all the farms

The highest predicted SOC stock was 60.15 Mg/ha for farmer 5 under conservation agriculture at 0-20 cm depth, while the lowest being 8.34 Mg/ha for farmer 1 under business-as-usual at 20-40 cm depth. The highest SOC stocks was for the farmer having initial carbon content further residue was retained on the soil surface thus increasing the SOC stocks at the surface layer. Lower carbon stocks at 20-40 cm depth could be due to soil texture due to sandy soils. This is in agreement with Adhikari and Bhattacharyya (2015) where, sandy soils was reported to have lower SOC stocks due to lower association on mineral surface thus exacerbating SOC stocks loss.

5.5.5 Average annual changes of SOC stocks per hectare per year

Conservation agriculture had a higher gain of SOC stocks compared to business-as-usual management due to more residue retained and reduced tillage. An increase in amount of crop residue retained increases organic matter into the soil while reduced tillage minimizes breakage of soil aggregates thus reduced the exposition of SOC stocks to decomposition. Arunrat *et al*. (2020) found that minimum tillage increases SOC stocks, particularly in the upper layer, compared to conventional tillage because of less disturbance from tillage operations.

The significant variability between farms is most likely a result of, first of all, differences in soil texture, as soil texture (above all clay content), is the single most driving factor of SOC under otherwise similar climatic and management conditions: Soil texture affects soil organic matter decomposition thus controlling SOC levels and carbon sequestration potential (Singh *et al*., 2018; Kimetu *et al*., 2008). Farm with soils with clay content has higher carbon stocks due to slow decomposition (Moussadek *et al*., 2014; Plante *et al*., 2006; Lal, 2004; Woomer and Mukhwana, 2004). Clay soils protect SOC from decomposition (Mujuru *et al*., 2016; Dunjana *et al*., 2012). Farm with high sand content had low carbon content since sand has a low organic matter association on mineral surfaces thus exacerbating SOC loss (Adhikari and Bhattacharyya, 2015). In addition, inputs added and initial carbon content – which is a consequence of time (years) of land use – adds to the observed differences among farms. Soil texture affects the decomposition process.

The quantity of organic input and fertilizers applied affects the amount of nutrients available for plant uptake. Since soils with high initial SOC have more substantial losses than soils with low initial SOC, the initial SOC stock is an essential factor controlling SOC stock changes when texture, climate and management practices are comparable (Wang *et al*., 2017).

Other management practices reported to increase SOC stocks include integrated nutrient management, agroforestry, crop rotation with legumes and soil and water conservation measures. The use of manure has been stated to increase SOC concentration (Aula *et al., 2016;* Mugwe *et al*., 2009; Kimetu *et al*., 2008; Mucheru-Muna *et al*., 2007; Bationo *et al*., 2006) with significant increased where manure was applied frequently over a prolonged period (Njoroge *et al*., 2019). According to a modeling study by Farage *et al*. (2007), adding farmyard manure could sequester 0.09 Mg/ha/yr, adoption of agroforestry (0.15 Mg/ha/yr) and zero tillage (up to 0.04 Mg/ha/yr) over the next 50 years.

5.6 Conclusion and Recommendations

The current study calibrated and validated CropSyst for Western Kenya, assessed SOC dynamics under business-as-usual scenario (existing farm practices), and compared this to a scenario where conservation agriculture (minimum tillage and full residue retention) was practiced. The model simulated SOC stocks reasonably well while it overestimated grain yields. The model revealed that business-as-usual management would deplete SOC stocks while adopting conservation agriculture would have a higher gain of SOC stocks. The model also revealed crop and nitrogen stress, with crop water stress being more prominent. Further, the highest gain (0.28 Mg/ha/yr) of SOC stocks at 0-20 cm depth was under conservation agriculture. The variability of SOC stocks over the years was due to fluctuating yields and biomass production. To improve and mantain SOC stocks among smallholder farming systems, conservation agriculture is the best management practice. Also, the replenishing of depleted nutrients through the application of organic and inorganic input is recommended. The model proved reliable in predicting SOC stocks among smallholder systems under different management practices therefore, can be used to identify appropriate management practices at the regional and broader scale level. However, long-term field studies are required to validate the model, which will allow for better monitoring of SOC stocks and their potential for sequestration. Therefore, field experiments, coupled with modeling, is crucial for identifying the best site-specific management practices.

Acknowledgements

This project was financed by International Centre for Tropical Agriculture (CIAT) under the BMZ project in collaboration with the University of Nairobi. Technical support from Land resource management and agricultural technology (LARMAT) department and ILRI, Mazingira centre is highly appreciated.

CHAPTER SIX: GENERAL DISCUSSION, CONCLUSION AND RECOMMENDATIONS

6.1 General Discussion

The study was undertaken to evaluate agricultural management practices among smallholder farmers of western Kenya and their influence on SOC stocks in Vihiga and Kakamega sub-Counties of western Kenya. The results show that the predominant agricultural management practice in Shikomoli and Mukuyu village was the use of manure in combination with chemical fertilizer with the highest SOC stocks under combination fertilizer, manure, and crop residue in both sites. Manure combined with chemical fertilizer as the main management practice is attributed to limited resources. Since chemical fertilizer is mainly applied in small quantities below the recommended levels of 60 kg N/ha and 30 kg P/ha (FAO and ITPS, 2015; Mugwe *et al*., 2009), manure is added to compensate for the inadequacy of chemical fertilizer. Castellanos-Navarrete *et al*. (2015) found a similar result in western Kenya, with farmers using manure as an alternative input to increase soil fertility and chemical fertilizer as a complementary nutrient substitute. The highest SOC stocks in both sites when fertilizer, manure, and crop residue were combined can be attributed to high organic matter additions from the manure and the residues from the crop. When chemical fertilizer, crop residue, and manure were added, Paul *et al*. (2015) and Berazneva *et al*. (2014) recorded higher SOC stocks, which was close to our findings.

The study sought further to determine the the effect of SOC stocks on soil physical and chemical properties. SOC stocks showed positive correlation with total nitrogen, carbon to nitrogen ratio, cation exchange capacity, silt, clay and manganese and negative correlation with sand and bulk density. This denotes that as SOC stocks increase the total nitrogen, carbon to nitrogen ratio, silt, clay and manganese increase. Hence, increased biomass production and crop yields through improved nutrient availability. Also, according increased cation exchange capacity increases the availability of other nutrients due to large surface area for adsorption of nutrients (Odour *et al*. 2018: Orgill *et al*. 2017; Srinivasaro *et al*. 2009).

Finally, the study sought to simulate SOC dynamics under business-as-usual and improved management scenarios. Over the predicted years (50 years), SOC stocks were predicted to decline for all the farms under business-as-usual management practice and increase in SOC stocks under conservation agriculture for all the farms. Conservation agriculture had a higher gain of SOC stocks compared to business-as-usual management due to more residue retained and reduced tillage. An increase in amount of crop residue retained increases organic matter into the soil while reduced tillage minimizes breakage of soil aggregates thus reduced the exposition of SOC stocks to decomposition. Arunrat *et al.* (2020) found that minimum tillage increases SOC stocks, particularly in the upper layer, compared to conventional tillage because of less disturbance from tillage operations. Also, results show variability of SOC stocks between farms. The significant variability between farms is most likely a result of, first of all, differences in soil texture, as soil texture (above all clay content), is the single most driving factor of SOC under otherwise similar climatic and management conditions. In addition, inputs added and initial carbon content – which is a consequence of time (years) of land use – adds to the observed differences among farms. Soil texture affects the decomposition process. The quantity of organic input and fertilizers applied affects the amount of nutrients available for plant uptake. Since soils with high initial SOC have more substantial losses than soils with low initial SOC, the initial SOC stock is an essential factor controlling SOC stock changes when texture, climate and management practices are comparable (Wang *et al*., 2017).

6.2Conclusion

The study established that the predominant management practice in both sites is use of chemical fertilizer in combination with manure with high SOC stocks reported under combination of manure, chemical fertilizer and crop residue. However, the current agricultural management practices would not sustain or improve SOC stocks in the long-term. Therefore, the need for adoption of cconservation agriculture as opposed to current management practices since it has a higher potential of carbon sequestration although dependent on the climate, soil texture and initial carbon content. In addition to adoption of conservation agriculture, it is necessary to incorporate practices including crop residue retention that increase organic matter content through high carbon input and reduced tillage. Also, management practices that increase TN, C/N ratio, CEC and Mn are necessary since they are crucial in carbon sequestration.

6.3. Recommendations

1. Smallholder farming systems in Vihiga and Kakamega, western Kenya need to adopt management practices that increase crop residue retention and minimize soil disturbance to avoid further loss in SOC stocks and yield
2. There is need to identify management practices that improve the physical and chemical properties at lower depths.
3. Long-term field studies are needed for model validation, resulting in better monitoring of SOC stocks and their capacity for sequestration.

REFERENCES

Adeoye, G. O., and Agboola, A. A. (1985). Critical levels for soil pH, available P, K, Zn and Mn and maize ear-leaf content of P, Cu and Mn in sedimentary soils of South-Western Nigeria. Fertilizer Research, 6(1), 65–71.

Adhikari, G., and Bhattacharyya, K. G. (2015). Correlation of soil organic carbon and nutrients (NPK) to soil mineralogy, texture, aggregation, and land use pattern. Environmental Monitoring and Assessment, 187(11), 1–18.

Adolwa, I. S., Okoth, P. F., Mulwa, R. M., Esilaba, A. O., Mairura, F. S., and Nambiro, E. (2012). Analysis of Communication and Dissemination Channels Influencing the Adoption of Integrated Soil Fertility Management in Western Kenya. Journal of Agricultural Education and Extension, 18(1), 71–86.

Ahmed, M. S., Zamir, M. R., and Sanaullah, A. F. M. (2005). Organic Carbon, Nitrogen and Phosphorus Contents of Some Tea Soils. Pak. J. Anal. Chem, *6*(1), 10–15.

Ajiboye, A. G., Aduloju, M. O., and Jaiyeola, O. A. (2015). Organic carbon fractions and micronutrient status of soils under some plantation crops in southwestern Nigeria. Archives of Agronomy and Soil Science, 61(8), 1089–1105.

Akinola, A. O., and Wissink, H. (2019). Trajectory of land reform in post-colonial African states. Springer Nature Switzerland AG.

Álvaro-Fuentes, J., Morell, F. J., Plaza-Bonilla, D., Arrúe, J. L., and Cantero-Martínez, C. (2012). Modelling tillage and nitrogen fertilization effects on soil organic carbon dynamics. Soil and Tillage Research, 120, 32–39.

Allen, D. E., Singh, B. P., and Dalal, R. C. (2011). Soil health indicators under climate change: a review of current knowledge. Soil health and climate change, 25-45.

Albrecht, A., Bullimore, J., Ball, A. S., Girvan, M. S., Pretty, J. N., Bossio, D. A., Scow, K. M., Osborn, A. M., Borelli, T., and Verchot, L. (2005). Soil Microbial Community Response to Land Use Change in an Agricultural Landscape of Western Kenya. Microbial Ecology, 49(1), 50–62.

Ariga, J., and Jayne, T. S. (2011). Fertilizer in Kenya: Factors Driving the Increase in Usage by Smallholder Farmers. In Yes Africa Can: Success Stories from a Dynamic Continent (Issue February 2015).

Arunrat, N., Pumijumnong, N., Sereenonchai, S., and Chareonwong, U. (2020). Factors controlling soil organic carbon sequestration of highland agricultural areas in the mae chaem basin, northern Thailand. Agronomy, 10(2), 305.

Asseng, S., Ewert, F., Rosenzweig, C., Jones, J. W., Hatfield, J. L., Ruane, A. C. and Wolf, J. (2013). Uncertainty in simulating wheat yields under climate change. Nature climate change, 3(9), 827-832.

Aula, L., Macnack, N., Omara, P., Mullock, J., and Raun, W. (2016). Effect of Fertilizer Nitrogen (N) on Soil Organic Carbon, Total N, and Soil pH in Long-Term Continuous Winter Wheat (Triticum Aestivum L.). Communications in Soil Science and Plant Analysis, 47(7), 863–874.

Ayuke, F. O., Six, J., Vanlauwe, B., Kibunja, C. N., Lelei, D. K., Pulleman, M. M., and Brussaard, L. (2011). Soil fertility management: Impacts on soil macrofauna, soil aggregation and soil organic matter allocation. Applied Soil Ecology, *48*(1), 53–62.

Azlan, A., Aweng, E. R., Ibrahim, C. O., and Noorhaidah, A. (2012). Correlation between soil organic matter, total organic matter and water content with climate and depths of soil at different land use in Kelantan, Malaysia. Journal of applied sciences and environmental management, 16(4).

Badini, O., Stöckle, C. O., Jones, J. W., Nelson, R., Kodio, A., and Keita, M. (2007). A simulation-based analysis of productivity and soil carbon in response to time-controlled rotational grazing in the West African Sahel region. Agricultural Systems, *94*(1), 87–96.

Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B., and Kimetu, J. (2006). Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agricultural Systems, 94(1), 13–25.

Bationo, A., Waswa, B. S., and Kihara, J. (2014). Soil carbon and agricultural productivity: perspectives from sub-Saharan Africa. Soil Carbon: Science, Management and Policy for Multiple Benefits, 132–140.

Bationo, A., Ngaradoum, D., Youl, S., Lompo, F., and Fening, J. O. (Eds.). (2018). Improving the Profitability, Sustainability and Efficiency of Nutrients Through Site Specific Fertilizer Recommendations in West Africa Agro-Ecosystems: Volume 1 (Vol. 1). Springer.

Batjes, N. H. (2010). Soil carbon stocks and projected changes according to land use and management: a case study for Kenya. Soil Use and Management, 20(3), 350–356.

Berazneva, J., Conrad, J. M., Güereña, D. T., Lehmann, J., and Woolf, D. (2014). Agricultural Productivity and Soil Carbon Dynamics: A Bioeconomic Model. American Journal of Agricultural Economics, 101(4), 1021–1046.

Benbi, D. K., and Brar, J. S. (2009). A 25-year record of carbon sequestration and soil properties. Agronomy for Sustainable Development, *29*, 257–265.

Bi, X., Li, B., Nan, B., Fan, Y., Fu, Q., and Zhang, X. (2018). Characteristics of soil organic carbon and total nitrogen under various grassland types along a transect in a mountain-basin system in Xinjiang, China. Journal of Arid Land, 10(4), 612–627.

Blanco-Canqui, H., and Lal, R. (2008). No-Tillage and Soil-Profile Carbon Sequestration: An On-Farm Assessment. Soil Science Society of America Journal, 72(3), 693.

Blake, G. R. (1965). Bulk density. Methods of Soil Analysis: Part 1 Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling, 9, 374-390.

Bryan, E., Ringler, C., Okoba, B., Koo, J., Herrero, M., and Silvestri, S. (2013). Can agriculture support climate change adaptation, greenhouse gas mitigation and rural livelihoods? insights from Kenya. Climatic Change, 118(2), 151–165.

Brown, T. T., and Huggins, D. R. (2012). Soil carbon sequestration in the dryland cropping region of the Pacific Northwest. Journal of Soil and Water Conservation, 67(5), 406–415.

Castellanos-Navarrete, A., Tittonell, P., Rufino, M. C., and Giller, K. E. (2015). Feeding, crop residue and manure management for integrated soil fertility management - A case study from Kenya. Agricultural Systems, 134, 24–35.

Cambardella, C. A., and Elliott, E. T. (1992). Particulate Soil Organic-Matter Changes across a Grassland Cultivation Sequence. Soil Science Society of America Journal, 56(3), 777–783.

Campos, R., Pires, G. F., and Costa, M. H. (2020). Soil carbon sequestration in rainfed and irrigated production systems in a new Brazilian agricultural frontier. Agriculture, 10(5), 156.

Chaudhari, P. R., Ahire, D. V., Ahire, V. D., Chkravarty, M., and Maity, S. (2013). Soil bulk density as related to soil texture, organic matter content and available total nutrients of Coimbatore soil. International Journal of Scientific and Research Publications, 3(2), 1-8.

Cheesman, S., Frossard, E., Kassie, G. T., Eash, N. S., and Thierfelder, C. (2016). Soil carbon stocks in conservation agriculture systems of Southern Africa. *Soil and Tillage Research*, *156*, 99–109.

Chikowo, R., Zingore, S., Snapp, S. and Johnston, A. (2014). Farm typologies, soil fertility variability and nutrient management in smallholder farming in Sub-Saharan Africa. Nutrient cycling in agroecosystems, 100(1), 1-18.

Coleman, K., and Jenkinson, D. S. (2005). RothC - A Model for the Turnover of Carbon in Soil: Model description and Users guide (DOS version; updated June 2014).

Cook, R. L., and Trlica, A. (2016). Tillage and fertilizer effects on crop yield and soil properties over 45 years in southern Illinois. Agronomy Journal, 108(1), 415-426.

Darwish, T., and Fadel, A. (2017). Mapping of soil organic carbon stock in the Arab countries to mitigate land degradation. Arabian Journal of Geosciences, 10(21), 1-11.

Day, P. R., and Luthin, J. N. (1956). A numerical solution of the differential equation of flow for a vertical drainage problem. Soil Science Society of America Journal, 20(4), 443- 447.

de Blécourt, M., Gröngröft, A., Baumann, S., and Eschenbach, A. (2019). Losses in soil organic carbon stocks and soil fertility due to deforestation for low-input agriculture in semi-arid southern Africa. Journal of Arid Environments, 165, 88-96.

Del Grosso, S., Ojima, D., Parton, W., Mosier, A., Peterson, G., and Schimel, D. (2002). Simulated effects of dryland cropping intensification on soil organic matter and greenhouse gas exchanges using the DAYCENT ecosystem model. Environmental pollution, 116, S75-S83.

Dhillon, J., Del Corso, M. R., Figueiredo, B., Nambi, E., and Raun, W. (2018). Soil Organic Carbon, Total Nitrogen, and Soil pH, in a Long-Term Continuous Winter Wheat (Triticum Aestivum L.) Experiment. Communications in Soil Science and Plant Analysis, 49(7), 803–813.

Diiro, G. M., Seymour, G., Kassie, M., Muricho, G. and Muriithi, B. W. (2018). Women's empowerment in agriculture and agricultural productivity: Evidence from rural maize farmer households in western Kenya. PloS one, 13(5), e0197995.

Diwani, T. N., Asch, F., Becker, M., and Mussgnug, F. (2016). Characterizing farming systems around Kakamega Forest, Western Kenya, for targeting soil fertility–enhancing technologies. Journal of Plant Nutrition and Soil Science, *176*(4), 585-594.

Don, A., Scholten, T., and Schulze, E. D. (2015). Conversion of cropland into grassland: Implications for soil organic-carbon stocks in two soils with different texture. Journal of Plant Nutrition and Soil Science, 172(1), 53–62.

Droppelmann, K. J., Snapp, S. S., and Waddington, S. R. (2017). Sustainable intensification options for smallholder maize-based farming systems in sub-Saharan Africa. Food Security, *9*(1), 133–150.

Dunjana, N., Nyamugafata, P., Shumba, A., Nyamangara, J., and Zingore, S. (2012). Effects of cattle manure on selected soil physical properties of smallholder farms on two soils of Murewa, Zimbabwe. Soil Use and Management, 28(2), 221–228.

Duval, M. E., Galantini, J. A., Martínez, J. M., and Limbozzi, F. (2018). Labile soil organic carbon for assessing soil quality: influence of management practices and edaphic conditions. Catena, 171, 316-326.

Ehui, S., & Pender, J. (2005). Resource degradation, low agricultural productivity, and poverty in sub-Saharan Africa: pathways out of the spiral. Agricultural Economics, 32, 225-242.

Eaton, J. M., McGoff, N. M., Byrne, K. A., Leahy, P., & Kiely, G. (2008). Land cover change and soil organic carbon stocks in the Republic of Ireland 1851–2000. Climatic change, 91(3), 317-334.

FAO, I. (2015). Status of the world’s soil resources (SWSR)–main report. Food and agriculture organization of the United Nations and intergovernmental technical panel on soils, Rome, Italy, 650.

FAO, and ITPS. (2015). Status of the World’s Soil Resources (SWSR) - Main Report. In Status of the World’s Soil Resources (SWSR) - Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome, Italy.

FAO 2017. Soil Organic Carbon: the hidden potential. Food and Agriculture Organization of the United Nations. Rome, Italy

Farage, P. K., Ardö, J., Olsson, L., Rienzi, E. A., Ball, A. S., and Pretty, J. N. (2007). The potential for soil carbon sequestration in three tropical dryland farming systems of Africa and Latin America: A modelling approach. Soil and Tillage Research, 94(2), 457–472.

Fontana, M., Berner, A., Mäder, P., Lamy, F., and Boivin, P. (2015). Soil Organic Carbon and Soil Bio-Physicochemical Properties as Co-Influenced by Tillage Treatment. Soil Science Society of America Journal, 79(5), 1435-1445.

Franko, U. (1996). Modelling approaches of soil organic matter turnover within the CANDY system. In Evaluation of soil organic matter models. Springer, Berlin, Heidelberg, 247-254.

Freibauer, A., Rounsevell, M. D. A., Smith, P., and Verhagen, J. (2004). Carbon sequestration in the agricultural soils of Europe. Geoderma, 122(1), 1–23.

Gebeyehu, G., and Soromessa, T. (2018). Status of soil organic carbon and nitrogen stocks in Koga Watershed Area, Northwest Ethiopia. Agriculture and Food Security, 7(1), 1–10.

Gollany, H. T., and Elnaggar, A. A. (2017). Simulating soil organic carbon changes across toposequences under dryland agriculture using CQESTR. Ecological Modelling, 355, 97-104.

Grace, P. R., Ladd, J. N., Robertson, G. P., and Gage, S. H. (2006). SOCRATES—a simple model for predicting long-term changes in soil organic carbon in terrestrial ecosystems. Soil Biology and Biochemistry, 38(5), 1172-1176.

Chang, K.-H., Warland, J., Voroney, P., Bartlett, P., and Wagner-Riddle, C. (2013). Using DayCENT to Simulate Carbon Dynamics in Conventional and No-Till Agriculture. Soil Science Society of America Journal, 77(3), 941–950.

Giller, K. E., Tittonell, P., Rufino, M. C., Van Wijk, M. T., Zingore, S., Mapfumo, P., ... and Vanlauwe, B. (2011). Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. Agricultural systems, 104(2), 191-203.

Gnanavelrajah, N., Shrestha, R. P., Schmidt-Vogt, D., and Samarakoon, L. (2008). Carbon stock assessment and soil carbon management in agricultural land-uses in Thailand. Land degradation & development, 19(3), 242-256.

Gomiero, T. (2016). Soil degradation, land scarcity and food security: Reviewing a complex challenge. Sustainability, 8(3), 281.

Guto, S. N., Pypers, P., Vanlauwe, B., de Ridder, N., and Giller, K. E. (2012). Socio-ecological niches for minimum tillage and crop-residue retention in continuous maize cropping systems in smallholder farms of central Kenya. Agronomy Journal, 104(1), 188–198.

Gupta, S., and Kumar, S. (2017). Simulating climate change impact on soil carbon sequestration in agro-ecosystem of mid-Himalayan landscape using CENTURY model. Environmental Earth Sciences, *76*(11), 1–15.

Han, P., Zhang, W., Wang, G., Sun, W., and Huang, Y. (2016). Changes in soil organic carbon in croplands subjected to fertilizer management: A global meta-analysis. Scientific reports, 6(1), 1-13.

Hashimoto, S., Ugawa, S., Morisada, K., Wattenbach, M., Smith, P., and Matsuura, Y. (2012). Potential carbon stock in Japanese forest soils - simulated impact of forest management and climate change using the CENTURY model. Soil Use and Management, *28*(1), 45–53.

Henao, J., and Baanante, C. (2006). Agricultural production and soil nutrient mining in Africa: Implications for resource conservation and policy development.

Horwath, W. R., and Kuzyakov, Y. (2018). The potential for soils to mitigate climate change through carbon sequestration. In Developments in Soil Science 35, (61-92).

Ichami, S. M., Shepherd, K. D., Sila, A. M., Stoorvogel, J. J., and Hoffland, E. (2019). Fertilizer response and nitrogen use efficiency in African smallholder maize farms. Nutrient Cycling in Agroecosystems, 113(1), 1–19.

Issaka, F., Zhang, Z., Zhao, Z. Q., Asenso, E., Li, J. H., Li, Y. T., and Wang, J. J. (2019). Sustainable conservation tillage improves soil nutrients and reduces nitrogen and phosphorous losses in maize farmland in southern China. Sustainability, 11(8), 2397.

Itabari, J. K., Njarui, D. M. G., and Kathuli, P. (2013, October). Soil fertility status, quality of available manure and its implication on soil fertility maintenance in the peri-urban areas of semi-arid eastern Kenya. In Joint Proceedings of the 27th Soil Science Society of East Africa and the 6th African Soil Science Society Conference.

Jackson, R. B., Lajtha, K., Crow, S. E., Hugelius, G., Kramer, M. G., and Piñeiro, G. (2017). The Ecology of Soil Carbon: Pools, Vulnerabilities, and Biotic and Abiotic Controls. Annual Review of Ecology, Evolution, and Systematics, 48(1), 419–445.

Jaetzold, R., Schmidt, H., Hornetz, B., and Shisanya, C. (2009). Vihiga and Kakamega. In *Farm Management Handbook of Kenya: Natural Conditions and Farm Management Information: Vol. II*.

Jiang, H., Han, X., Zou, W., Hao, X., and Zhang, B. (2018). Seasonal and long-term changes in soil physical properties and organic carbon fractions as affected by manure application rates in the Mollisol region of Northeast China. Agriculture, Ecosystems and Environment, *268*, 133–143.

Johnson, K., Purvis, G., Lopez-Capel, E., Peacock, C., Gray, N., Wagner, T., ... & Greenwell, C. (2015). Towards a mechanistic understanding of carbon stabilization in manganese oxides. Nature communications, 6(1), 1-11.

Johannes, A., Matter, A., Schulin, R., Weisskopf, P., Baveye, P. C., and Boivin, P. (2017). Optimal organic carbon values for soil structure quality of arable soils. Does clay content matter? Geoderma, 302, 14–21.

Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., Wilkens, P. W., Singh, U., Gijsman, A. J., and Ritchie, J. T. (2003). The DSSAT cropping system model. In European Journal of Agronomy, 18, 3–4.

Kabirinejad, S., Kalbasi, M., Khoshgoftarmanesh, A. H., Hoodaji, M., and Afyuni, M. (2014). Effect of Incorporation of Crops Residue into Soil on Some Chemical Properties of Soil and Bioavailability of Copper in Soil. International Journal of Advanced Biological and Biomedical Research, 2(11), 2819–2824.

KALRO-KCEP. (2016). KALRO-KCEP soil fertility management training and extension manual

Kane, D., & Solutions, L. L. C. (2015). Carbon sequestration potential on agricultural lands: a review of current science and available practices. National Sustainable Agriculture Coalition Breakthrough Strategies and Solutions, LLC, 1-35.

Kanyanjua, S. M., Ireri, L., Wambua, S., and Nandwa, S. M. (2002). Acidic soils in Kenya: Constraints and remedial options.

Kätterer, T., Roobroeck, D., Andrén, O., Kimutai, G., Karltun, E., Kirchmann, H., … Röing de Nowina, K. (2019). Biochar addition persistently increased soil fertility and yields in maize-soybean rotations over 10 years in sub-humid regions of Kenya. Field Crops Research, 235, 18–26.

Kimetu, J. M., Lehmann, J., Ngoze, S. O., Mugendi, D. N., Kinyangi, J. M., Riha, S., ... & Pell, A. N. (2008). Reversibility of soil productivity decline with organic matter of differing quality along a degradation gradient. Ecosystems, 11(5), 726-739.

Kisinyo, P. O., Opala, P. A., Palapala, V., Gudu, S. O., Othieno, C. O., and Ouma, E. (2015). Micro-Dosing of Lime, Phosphorus and Nitrogen Fertilizers Effect on Maize Performance on an Acid Soil in Kenya. Sustainable Agriculture Research, 4(2), 21.

Kumar, S., Meena, R. S., Parihar, M., Jatav, H. S., and Jatav, S. S. (2016). Agricultural fields: A great sink Potential of Carbon Sequestration. Agriculture for Sustainable Development, 3-4.

Kuyah, S., Whitney, C. W., Jonsson, M., Sileshi, G. W., Öborn, I., Muthuri, C. W., and Luedeling, E. (2019). Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis. *Agronomy for Sustainable Development*, *39*(5).

Kweyu, S. (2017). How can rural economies be revamped through empowering smallholder farmers? A case of Western Kenya. International Journal of Social Science and Economic Research, 2(05), 3380–3400.

Kwon, H., Ugarte, C. M., Ogle, S. M., Williams, S. A., and Wander, M. M. (2017). Use of inverse modeling to evaluate CENTURY-predictions for soil carbon sequestration in US rain-fed corn production systems. PLoS ONE, 12(2), 1–18.

Lal, R. (2004). A Review of the Agroforestry Systems of Costa Rica. Journal of Sustainable Forestry, 21(1), 97–119.

Lal, Rattan. (2004). Carbon sequestration in dryland ecosystems. Environmental Management, 33(4), 528–544.

Lal, Rattan. (2006). … Countries Through Restoration of the Soil Organic Carbon Pool in Agricultural Lands. Land Degradation and Development, 209, 197–209.

Lal, Rattan. (2016). Soil health and carbon management. Food and Energy Security, 5(4), 212–222.

Landon, J. R. (1991). Booker Tropical Soil Manual: a handbook for soil survey and agricultural land evaluation in the tropics and subtropics. (eds.) John Wiley and Sons Inc. New York.

Lee, J. (2017). Farmer participation in a climate-smart future: Evidence from the Kenya agricultural carbon market project. Land Use Policy, 68, 72–79.

Lemma, B., Kleja, D. B., Nilsson, I., and Olsson, M. (2006). Soil carbon sequestration under different exotic tree species in the southwestern highlands of Ethiopia. Geoderma, 136(3–4), 886–898.

Lemenih, M., Karltun, E., and Olsson, M. (2005). Assessing soil chemical and physical property responses to deforestation and subsequent cultivation in smallholders farming system in Ethiopia. Agriculture, Ecosystems and Environment, 105(1–2), 373–386.

Li, J., Wen, Y., Li, X., Li, Y., Yang, X., Lin, Z., Song, Z., Cooper, J. M., and Zhao, B. (2018). Soil labile organic carbon fractions and soil organic carbon stocks as affected by long-term organic and mineral fertilization regimes in the North China Plain. Soil and Tillage Research, 175(August 2017), 281–290.

Liu, E., Yan, C., Mei, X., Zhang, Y., and Fan, T. (2013). Long-Term Effect of Manure and Fertilizer on Soil Organic Carbon Pools in Dryland Farming in Northwest China. *PLoS ONE*, *8*(2).

Liang, F., Li, J., Yang, X., Huang, S., Cai, Z., Gao, H., Ma, J., Cui, X., and Xu, M. (2016). Three-decade long fertilization-induced soil organic carbon sequestration depends on edaphic characteristics in six typical croplands. Scientific Reports, 6, 1–12.

Liu, S., Zhang, Y., Zong, Y., Hu, Z., Wu, S., Zhou, J., Jin, Y., and Zou, J. (2016). Response of soil carbon dioxide fluxes, soil organic carbon and microbial biomass carbon to biochar amendment: A meta-analysis. GCB Bioenergy, 8(2), 392–406.

Liu, M., Han, G., and Zhang, Q. (2019). Effects of soil aggregate stability on soil organic carbon and nitrogen under land use change in an erodible region in southwest China. International Journal of Environmental Research and Public Health, 16(20).

Mahajan, G. R., Das, B., Manivannan, S., Manjunath, B. L., Verma, R. R., Desai, S., ... and Mulla, H. (2021). Soil and water conservation measures improve soil carbon sequestration and soil quality under cashews. International Journal of Sediment Research, 36(2), 190-206.

Maillard, É., Angers, D. A., Centre, D., Canada, A., and Comtois, P. P. (2014). Animal manure application and soil organic carbon stocks: A meta-analysis. Global Change Biology, 20(2), 666–679.

Makumba, W., Akinnifesi, F. K., Janssen, B., and Oenema, O. (2007). Long-term impact of a gliricidia-maize intercropping system on carbon sequestration in southern Malawi. Agriculture, Ecosystems and Environment, 118(1–4), 237–243.

Maltas, A., Kebli, H., Oberholzer, H. R., Weisskopf, P., and Sinaj, S. (2018). The effects of organic and mineral fertilizers on carbon sequestration, soil properties, and crop yields from a long-term field experiment under a Swiss conventional farming system. Land Degradation and Development, 29(4), 926–938.

Mangalassery, S., Kalaivanan, D., and Philip, P. S. (2019). Effect of inorganic fertilisers and organic amendments on soil aggregation and biochemical characteristics in a weathered tropical soil. Soil and Tillage Research, 187, 144–151.

Manna, M., Rao, A., and Mandal, A. (2015). Impact of agricultural land management practices on soil carbon sequestration. Indian Journal of Soil Conservation, 43(3), 204–212.

Marenya, P. P., and Barrett, C. B. (2009). Soil quality and fertilizer use rates among smallholder farmers in western Kenya. Agricultural Economics, 40(5), 561-572.

Mathew, I., Shimelis, H., Mutema, M., and Chaplot, V. (2017). What crop type for atmospheric carbon sequestration: Results from a global data analysis. Agriculture, Ecosystems and Environment, 243, 34–46.

Masvaya, E. N., Nyamangara, J., Nyawasha, R. W., Zingore, S., Delve, R. J., and Giller, K. E. (2010). Effect of farmer management strategies on spatial variability of soil fertility and crop nutrient uptake in contrasting agro-ecological zones in Zimbabwe. Nutrient Cycling in Agroecosystems, 88(1), 111–120.

Merante, P., Dibari, C., Ferrise, R., Sánchez, B., Iglesias, A., Lesschen, J. P., Kuikman, P., Yeluripati, J., Smith, P., and Bindi, M. (2017). Adopting soil organic carbon management practices in soils of varying quality: Implications and perspectives in Europe. Soil and Tillage Research, 165, 95–106.

Misiko, M., Tittonell, P., Giller, K. E., and Richards, P. (2011). Strengthening understanding and perceptions of mineral fertilizer use among smallholder farmers: Evidence from collective trials in western Kenya. Agriculture and Human Values, 28(1), 27–38.

Moebius-Clune, B. N., van Es, H. M., Idowu, O. J., Schindelbeck, R. R., Kimetu, J. M., Ngoze, S., Lehmann, J., and Kinyangi, J. M. (2011). Long-term soil quality degradation along a cultivation chronosequence in western Kenya. Agriculture, Ecosystems and Environment, 141(1–2), 86–99.

Moebius-clune, B. N., van Es, H. M., Idowu, O. J., Schindelbeck, R. R., Kimetu, J. M., Ngoze, S., Lehmann, J., Kinyangi, J. M., Es, H. M. Van, Idowu, O. J., Schindelbeck, R. R., and Kimetu, J. M. (2011). Long-term soil quality degradation along a cultivation chronosequence in western Kenya. Agriculture, Ecosystems and Environment, 141(1–2), 86–99.

Morgan, J. A., Franzluebbers, A., Schoeneberger, M. M., Derner, J. D., Dijkstra, F., Allen, L. H., Follett, R. F., Fry, R., Del Grosso, S., and Paustian, K. (2010). Carbon sequestration in agricultural lands of the United States. Journal of Soil and Water Conservation, 65(1), 6A-13A.

Moussadek, R., Mrabet, R., Dahan, R., Zouahri, A., El Mourid, M., and Ranst, E. V. (2014). Tillage system affects soil organic carbon storage and quality in Central Morocco. Applied and Environmental Soil Science, 2014.

Mtangadura, T. J., Mtambanengwe, F., Nezomba, H., Rurinda, J., and Mapfumo, P. (2017). Why organic resources and current fertilizer formulations in Southern Africa cannot sustain maize productivity: Evidence from a long-term experiment in Zimbabwe. PLoS ONE, 12(8), 1–23.

Mucheru-Muna, M., Mugendi, D., Kung'u, J., Mugwe, J., and Bationo, A. (2007). Effects of organic and mineral fertilizer inputs on maize yield and soil chemical properties in a maize cropping system in Meru South District, Kenya. Agroforestry Systems, 69(3), 189–197.

Mueller, T., Jensen, L. S., Hansen, S., & Nielsen, N. E. (1996). Simulating soil carbon and nitrogen dynamics with the soil-plant-atmosphere system model DAISY. In Evaluation of Soil Organic Matter Models, 275-281.

Mugwe, B. J., Mugendi, D., Mucheru-muna, M., Merckx, R., Chianu, J., and Vanlauwe, B. (2009). Determinants Of the Decision to adopt Integrated Soil Fertility Management Practices by Smallholder Farmers in The Central Highlands of Kenya. Expl Agric., 45, 61–75.

Mujuru, L., Rusinamhodzi, L., Nyamangara, J., and Hoosbeek, M. R. (2016). Effects of nitrogen fertilizer and manure application on storage of carbon and nitrogen under continuous maize cropping in Arenosols and Luvisols of Zimbabwe. Journal of Agricultural Science, 154(2), 242–257.

Muktar, M., Bobe, B., Kibebew, K., and Yared, M. (2018). Soil organic carbon stock under different land use types in Kersa Sub Watershed, Eastern Ethiopia. African Journal of Agricultural Research, 13(24), 1248–1256.

Muktar, M., Bobe, B., Kibebew, K., and Yared, M. (2018). Soil organic carbon stock under different land use types in Kersa Sub Watershed, Eastern Ethiopia. African Journal of Agricultural Research, 13(24), 1248–1256.

Munialo, S., Ola, H., Maria, F. A. B., Niklas, B. O., Cecilia, O. M., Willis, O. K., … Djurfeldt, G. (2019). Micro-spatial analysis of maize yield gap variability and production factors on smallholder farms. Agriculture (Switzerland), 9(10), 1–23.

Muñoz-Rojas, M., Jordán, A., Zavala, L. M., González-Peñaloza, F. A., De La Rosa, D., Pino-Mejias, R., and Anaya-Romero, M. (2013). Modelling soil organic carbon stocks in global change scenarios: A CarboSOIL application. Biogeosciences, 10(12), 8253–8268.

Munthali, M. G., Gachene, C. K., Karanja, N. K., and G.W., S. (2015). Decomposition Rates and Nutrient Release Patterns of Tephrosia vogelii and Tephrosia candida Residues in Malawi. International Journal of Plant Research, 1(2), 26–35.

Musinguzi, P., Ebanyat, P., Tenywa, J. S., Basamba, T. A., Tenywa, M. M., and Mubiru, D. (2015). Precision of farmer-based fertility ratings and soil organic carbon for crop production on a Ferralsol. Solid Earth, 6(3), 1063–1073.

Musinguzi, Patrick, Ebanyat, P., Tenywa, J. S., Mwanjalolo, M., and Basamba, T. A. (2014). under a low-input maize cropping system Using DSSAT-CENTURY Model to Simulate Soil Organic Carbon Dynamics Under a Low-Input Maize Cropping System.

Musinguzi, Patrick, Tenywa, J. S., Ebanyat, P., Tenywa, M. M., Mubiru, D. N., Basamba, T. A., and Leip, A. (2013). Soil Organic Carbon Thresholds and Nitrogen Management in Tropical Agroecosystems: Concepts and Prospects. Journal of Sustainable Development, 6(12), 31–43.

Nandwa, S. M. (2001). Soil organic carbon (SOC) management for sustainable productivity of cropping and agro-forestry systems in Eastern and Southern Africa. Nutrient Cycling in Agroecosystems, 61(1–2), 143–158.

National Accelerated Agricultural Inputs Access Programme (NAAIAP), and Kenya Agrcultural Research Institute (KARI). (2014). Soil suitability evaluation for maize production in Kenya:A Report by National Accelerated Agricultural Inputs Access Programme (NAAIAP) in collaboration with Kenya Agricultural Research Institute (KARI) Department of Kenya Soil Survey.

Ngetich, F., Mugendi, D. N., Mugwe, J. N., and Vanlauwe, B. (2009). Soil chemical properties as influenced by organic inputs and mineral fertilizer in Mbeere District , Kenya. Joint Proceedings of the 27th Soil Science Society of East Africa and the 6th African Soil Science Society, 1–8.

Ngome, A. F. E., Becker, M., and Mtei, K. M. (2011). Leguminous cover crops differentially affect maize yields in three contrasting soil types of Kakamega, Western Kenya. Journal of Agriculture and Rural Development in the Tropics and Subtropics, 112(1), 1–10.

Njoroge, S., Schut, A. G. T., Giller, K. E., and Zingore, S. (2019). Learning from the soil's memory: Tailoring of fertilizer application based on past manure applications increases fertilizer use efficiency and crop productivity on Kenyan smallholder farms. European Journal of Agronomy, 105, 52–61.

Nkonya, E., Mirzabaev, A., and Von Braun, J. (2015). Institutional framework of (in) action against land degradation. In Economics of Land Degradation and Improvement - A Global Assessment for Sustainable Development, 33–54.

Nwaogu, C., Okeke, O. J., Fashae, O., and Nwankwoala, H. (2018). Soil organic carbon and total nitrogen stocks as affected by different land use in an Ultisol in Imo Watershed, southern Nigeria. Chemistry and Ecology, 34(9), 854–870.

Nyawira, S. S. (2019). Crop and soil organic matter simulation models – A brief review of their basic features and application in sub-Saharan Africa. In Research Brief. International Center for Tropical Agriculture, Nairobi, Kenya (Issue December).

Nyberg, G., Bargués Tobella, A., Kinyangi, J., and Ilstedt, U. (2012). Soil property changes over a 120-yr chronosequence from forest to agriculture in western Kenya. Hydrology and Earth System Sciences, 16(7), 2085–2094.

Odhiambo, J. A., Norton, U., Ashilenje, D., Omondi, E. C., and Norton, J. B. (2015). Weed dynamics during transition to conservation agriculture in western Kenya maize production. PLoS ONE, 10(8), 1–13.

Oduor, C. O., Karanja, N. K., Onwonga, R. N., Mureithi, S. M., Pelster, D., and Nyberg, G. (2018). Enhancing soil organic carbon, particulate organic carbon and microbial biomass in semi-arid rangeland using pasture enclosures. BMC ecology, 18(1), 1-9.

Ojiem, J. O., De Ridder, N., Vanlauwe, B., and Giller, K. E. (2006). Socio-ecological niche: a conceptual framework for integration of legumes in smallholder farming systems. International Journal of Agricultural Sustainability, 4(1), 79-93.

Okeyo, J. M., Norton, J., Koala, S., Waswa, B., Kihara, J., and Bationo, A. (2016). Impact of reduced tillage and crop residue management on soil properties and crop yields in a long-term trial in western Kenya. Soil Research, 54(6), 719–729.

Omamo, S. W., Williams, J. C., Obare, G. A., and Ndiwa, N. N. (2002). Soil fertility management on small farms in Africa: Evidence from Nakuru District, Kenya. *Food Policy*, *27*(2), 159–170.

Orgill, S. E., Condon, J. R., Conyers, M. K., Morris, S. G., Murphy, B. W., and Greene, R. S. B. (2017). Parent material and climate affect soil organic carbon fractions under pastures in south-eastern Australia. Soil Research, 55(8), 799–808.

Orgill, S. E., Condon, J. R., Conyers, M. K., Morris, S. G., Murphy, B. W., and Greene, R. S. B. (2017). Parent material and climate affect soil organic carbon fractions under pastures in south-eastern Australia. Soil Research, 55(8), 799–808.

Pal, S., and Marschner, P. (2016). Influence of clay concentration, residue C/N and particle size on microbial activity and nutrient availability in clay-amended sandy soil. Journal of soil science and plant nutrition, 16(2), 350-361.

Pan, C., Zhao, H., Zhao, X., Han, H., Wang, Y., and Li, J. (2013a). Biophysical Properties as Determinants for Soil Organic Carbon and Total Nitrogen in Grassland Salinization. PLoS ONE, 8(1), 1–6.

Pan, C., Zhao, H., Zhao, X., Han, H., Wang, Y., and Li, J. (2013). Biophysical properties as determinants for soil organic carbon and total nitrogen in grassland salinization. PloS one, 8(1), e54827.

Pandiaraj, T., Selvaraj, S., and Ramu, N. (2000). Effects of Crop Residue Management and Nitrogen Fertilizer on Soil Nitrogen and Carbon Content and Productivity of Wheat (Triticum aestivum L.) in Two Cropping Systems. Journal of Agricultural Science and Technology, 17(2015), 249–260.

Parton, W. J. (1996). The CENTURY model. In Evaluation of Soil Organic Matter Models, 283–291.

Paul, B. K., Vanlauwe, B., Hoogmoed, M., Hurisso, T. T., Ndabamenye, T., Terano, Y., … Pulleman, M. M. (2015). Exclusion of soil macrofauna did not affect soil quality but increased crop yields in a sub-humid tropical maize-based system. Agriculture, Ecosystems and Environment, 208, 75–85.

Piikki, K., Söderström, M., Sommer, R., Silva, M. Da, Munialo, S., and Abera, W. (2019). A Boundary Plane Approach to Map Hotspots for Achievable Soil Carbon Sequestration and Soil Fertility Improvement. Sustainability, 1–17.

Place, F., Barrett, C. B., Freeman, H. A., Ramisch, J. J., and Vanlauwe, B. (2003). Prospects for integrated soil fertility management using organic and inorganic inputs: Evidence from smallholder African agricultural systems. Food Policy, 28(4), 365–378.

Plante, A. F., Conant, R. T., Stewart, C. E., Paustian, K., and Six, J. (2006). Impact of Soil Texture on the Distribution of Soil Organic Matter in Physical and Chemical Fractions, 287–296.

Poeplau, C., and Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops - A meta-analysis. Agriculture, Ecosystems and Environment, 200, 33–41.

Poeplau, C., Reiter, L., Berti, A., and Kätterer, T. (2017). Qualitative and quantitative response of soil organic carbon to 40 years of crop residue incorporation under contrasting nitrogen fertilisation regimes. Soil Research, 55(1), 1–9.

Powers, J. S., and Schlesinger, W. H. (2002). Relationships among soil carbon distributions and biophysical factors at nested spatial scales in rain forests of northeastern Costa Rica. Geoderma, 109(3–4), 165–190.

Powlson, D. S., Stirling, C. M., Thierfelder, C., White, R. P., and Jat, M. L. (2016). Agriculture, Ecosystems and Environment Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? “Agriculture, Ecosystems and Environment,” 220, 164–174.

Raffa,Warrafa, D., Bogdanski, A., and Tittonell, P. (2015). How does crop residue removal affect soil organic carbon and yield? A hierarchical analysis of management and environmental factors. Biomass and Bioenergy, 81, 345–355.

Rahangdale, C. P., Nehru, J., Vishwavidyalaya, K., and Bisen, N. (2018). Physico-chemical properties and organic carbon stock in a Vertisol as influenced by different land use systems. International Journal of Chemical Studies, 6, 244–249.

Ratnayake, R. R., Kugendren, T., and Gnanavelrajah, N. (2014). Changes in soil carbon stocks under different agricultural management practices in North Sri Lanka. Journal of the National Science Foundation of Sri Lanka, 42(1), 37–44.

Ren, T., Wang, J., Chen, Q., Zhang, F., and Lu, S. (2014). The effects of manure and nitrogen fertilizer applications on soil organic carbon and nitrogen in a high-input cropping system. PLoS ONE, 9(5).

Rinaldi, M., Scalcione, E., Perniola, M., Maddaluno, C., and Garofalo, P. (2017). Soil tillage and residues management in wheat continuous cropping in Southern Italy: A model application for agronomic and soil fertility assessment. Computers and Electronics in Agriculture, 140, 77–87.

Rutkowska, A., and Pikuła, D. (2013). Effect of Crop Rotation and Nitrogen Fertilization on the Quality and Quantity of Soil Organic Matter. Soil Processes and Current Trends in Quality Assessment, 249–267.

Saiz, G., Bird, M. I., Domingues, T., Schrodt, F., Schwarz, M., Feldpausch, T. R., Veenendaal, E., Djagbletey, G., Hien, F., Compaore, H., Diallo, A., and Lloyd, J. (2012). Variation in soil carbon stocks and their determinants across a precipitation gradient in West Africa. Global Change Biology, 18(5), 1670–1683.

Salat, M., and Swallow, B. (2018). Resource Use Efficiency as a Climate Smart Approach: Case of Smallholder Maize Farmers in Nyando, Kenya. Environments, 5(8), 93.

Sanderman, J., and Baldock, J. A. (2010). Accounting for soil carbon sequestration in national inventories: A soil scientist's perspective. Environmental Research Letters, 5(3).

Schweizer, S. A., Seitz, B., van der Heijden, M. G. A., Schulin, R., and Tandy, S. (2018). Impact of organic and conventional farming systems on wheat grain uptake and soil bioavailability of zinc and cadmium. Science of the Total Environment, 639, 608–616.

Shah, S., and Andrabi, S. G. J. (2009). Micronutrient cation studies of some paddy growing soils of Kashmir. *Asian Journal of Soil Science*, *4*(2), 165-167.

Shelukindo, H. ., Msanya, B., Singh, R. ., and Munishi, P. K. . (2014). Predictor variables for soil organic carbon contents in the Miombowoodlands ecosystem of Kitonga forest reserve, Tanzania. International Journal of Agricultural Sciences, 4(7), 2167–2447.

Sileshi, M., Kadigi, R., Mutabazi, K., and Sieber, S. (2019). Determinants for adoption of physical soil and water conservation measures by smallholder farmers in Ethiopia. International Soil and Water Conservation Research, 7(4), 354–361.

Singh, B. P., Setia, R., Wiesmeier, M., and Kunhikrishnan, A. (2018). Agricultural Management Practices and Soil Organic Carbon Storage. In Soil Carbon Storage, 207–244.

Six, J., Elliott, E. T., and Paustian, K. (2000). Soil Structure and Soil Organic Matter. Soil Science Society of America Journal, 64(3), 681–689.

Singh, M., Sarkar, B., Sarkar, S., Churchman, J., Bolan, N., Mandal, S., ... and Beerling, D. J. (2018). Stabilization of soil organic carbon as influenced by clay mineralogy. Advances in agronomy, 148, 33-84.

Soler, C. M. T., Bado, V. B., Traore, K., Bostick, W. M., Jones, J. W., and Hoogenboom, G. (2011). Soil organic carbon dynamics and crop yield for different crop rotations in a degraded ferruginous tropical soil in a semi-arid region: A simulation approach. Journal of Agricultural Science, 149(5), 579–593.

Sombrero, A., and de Benito, A. (2010). Carbon accumulation in soil. Ten-year study of conservation tillage and crop rotation in a semi-arid area of Castile-Leon, Spain. Soil and Tillage Research, 107(2), 64–70.

Sommer, R. (2011). Information Sheet On Future Climate And Impacts In The Rural Case Studies: Tel Hadya, Syria.

Sommer, R. (2017). Model-based assessment of soil organic carbon dynamics and potentials for carbon sequestration under integrated soil fertility management and conservation agriculture in Western Kenya. April, 1–13.

Sommer, R., Paul, B. K., Mukalama, J., and Kihara, J. (2018). Reducing losses but failing to sequester carbon in soils – the case of Conservation Agriculture and Integrated Soil Fertility Management in the humid tropical agro-ecosystem of Western Kenya. Agriculture, Ecosystems and Environment, 254, 82–91.

Song, X., Bryan, B. A., Luo, Z., Yu, Q., Zhao, G., King, D., and Wang, E. (2013). Impact of agricultural management practices on soil organic carbon: simulation of Australian wheat systems. Global Change Biology, 19(5), 1585–1597.

Soracco, C. G., Lozano, L. A., Villarreal, R., Palancar, T. C., Collazo, D. J., Sarli, G. O., and Filgueira, R. R. (2015). Effects of compaction due to machinery traffic on soil pore configuration. Revista Brasileira de Ciência do Solo, 39(2), 408-415.

Srinivasarao, C., Vittal, K. P. R., Venkateswarlu, B., Wani, S. P., Sahrawat, K. L., Marimuthu, S., and Kundu, S. (2009). Carbon stocks in different soil types under diverse rainfed production systems in tropical India. Communications in Soil Science and Plant Analysis, 40(15–16), 2338–2356.

Stahl, C., Blanfort, V., Burban, B., Ponchant, L., Dezécache, C., Picon-Cochard, C., Bonal, D., Soussana, J.-F., Klumpp, K., Grise, M. M., Fontaine, S., Freycon, V., and Blanc, L. (2016). Continuous soil carbon storage of old permanent pastures in Amazonia. Global Change Biology, 23(8), 3382–3392.

Stendahl, J., Berg, B., and Lindahl, B. D. (2017). Manganese availability is negatively associated with carbon storage in northern coniferous forest humus layers. Scientific Reports, 7(1), 1–6.

Steward, P. R., Dougill, A. J., Thierfelder, C., Pittelkow, C. M., Stringer, L. C., Kudzala, M., and Shackelford, G. E. (2018). The adaptive capacity of maize-based conservation agriculture systems to climate stress in tropical and subtropical environments: A meta-regression of yields. Agriculture, Ecosystems and Environment, *251*, 194–202.

Stewart, C. E., Paustian, K., Conant, R. T., Plante, A. F., and Six, J. (2007). Soil carbon saturation: concept, evidence and evaluation. Biogeochemistry, *86*(1), 19-31.

Stöckle, C. O., Donatelli, M., and Nelson, R. (2003). CropSyst, a cropping systems simulation model. European Journal of Agronomy, 18(3–4), 289–307.

Stöckle, C., Higgins, S., Kemanian, A., Nelson, R., Huggins, D., Marcos, J., and Collins, H. (2012). Carbon storage and nitrous oxide emissions of cropping systems in eastern Washington: A simulation study. Journal of Soil and Water Conservation, *67*(5), 365-377.

Su, Y. Z., Wang, F., Suo, D. R., Zhang, Z. H., and Du, M. W. (2006). Long-term effect of fertilizer and manure application on soil-carbon sequestration and soil fertility under the wheat-wheat-maize cropping system in northwest China. Nutrient Cycling in Agroecosystems, 75(1–3), 285–295.

Swanepoel, C. M., Rötter, R. P., Van der Laan, M., Annandale, J. G., Beukes, D. J., du Preez, C. C., ... and Hoffmann, M. P. (2018). The benefits of conservation agriculture on soil organic carbon and yield in southern Africa are site-specific. Soil and Tillage Research, *183*, 72-82.

Thierfelder, C., Mwila, M., and Rusinamhodzi, L. (2013). Conservation agriculture in eastern and southern provinces of Zambia: Long-term effects on soil quality and maize productivity. Soil and Tillage Research, 126, 246–258.

Thomson, A. M., Izaurralde, R. C., Rosenberg, N. J., and He, X. (2006). Climate change impacts on agriculture and soil carbon sequestration potential in the Huang-Hai Plain of China. Agriculture, Ecosystems and Environment, 114(2–4), 195–209.

Tittonell, P., Corbeels, M., Van Wijk, M. T., Vanlauwe, B., and Giller, K. E. (2008). Combining organic and mineral fertilizers for integrated soil fertility management in smallholder farming systems of Kenya: Explorations using the crop-soil model FIELD. Agronomy Journal, 100(5), 1511–1526.

Tittonell, P., Vanlauwe, B., Leffelaar, P. A., Rowe, E. C., and Giller, K. E. (2005). Exploring diversity in soil fertility management of smallholder farms in western Kenya: I. Heterogeneity at region and farm scale. Agriculture, Ecosystems and Environment, 110(3–4), 149–165.

Tittonell, Pablo, Rufino, M. C., Janssen, B. H., and Giller, K. E. (2010). Carbon and nutrient losses during manure storage under traditional and improved practices in smallholder crop-livestock systems-evidence from Kenya. Plant and Soil, 328(1), 253–269.

Tolessa, T., and Senbeta, F. (2018). The extent of soil organic carbon and total nitrogen in forest fragments of the central highlands of Ethiopia. Journal of Ecology and Environment, 4, 1–11.

Touré, A., Temgoua, E., Guenat, C., and Elberling, B. (2013). Land use and soil texture effects on organic carbon change in dryland soils, Senegal. Open Journal of Soil Science, *3*(6), 253-262.

Tsozué, D., Nghonda, J. P., Tematio, P., and Basga, S. D. (2019). Changes in soil properties and soil organic carbon stocks along an elevation gradient at Mount Bambouto, Central Africa. Catena, 175, 251–262.

Tully, K., Sullivan, C., Weil, R., and Sanchez, P. (2015). The State of soil degradation in sub-Saharan Africa: Baselines, trajectories, and solutions. Sustainability (Switzerland), 7(6), 6523–6552.

Turmel, M. S., Speratti, A., Baudron, F., Verhulst, N., and Govaerts, B. (2015). Crop residue management and soil health: A systems analysis. Agricultural Systems, 134, 6-16.

Vågen, T. G., Ann Winowiecki, L., Neely, C., Chesterman, S., and Bourne, M. (2018). Spatial assessments of soil organic carbon for stakeholder decision-making - A case study from Kenya. Soil, 4(4), 259–266.

Valdez, Z. P., Hockaday, W. C., Masiello, C. A., Gallagher, M. E., and Philip Robertson, G. (2017). Soil Carbon and Nitrogen Responses to Nitrogen Fertilizer and Harvesting Rates in Switchgrass Cropping Systems. Bioenergy Research, 10(2), 456–464.

Valbuena, D., Groot, J. C. J., Mukalama, J., Gérard, B., and Tittonell, P. (2015). Improving rural livelihoods as a "moving target": trajectories of change in smallholder farming systems of Western Kenya. Regional Environmental Change, *15*(7), 1395–1407.

Vanlauwe, B., Descheemaeker, K., Giller, K. E., Huising, J., Merckx, R., Nziguheba, G., ... and Zingore, S. (2015). Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. Soil, *1*(1), 491-508.

Vesterdal, L., Ritter, E., and Gundersen, P. (2002). Change in soil organic carbon following afforestation of former arable land. Forest ecology and management, *169*(1-2), 137-147.

Waithaka, M. M., Thornton, P. K., Shepherd, K. D., and Ndiwa, N. N. (2007). Factors affecting the use of fertilizers and manure by smallholders: The case of Vihiga, western Kenya. Nutrient Cycling in Agroecosystems, 78(3), 211–224.

Wan, Y., Lin, E., Xiong, W., and Guo, L. (2011). Modeling the impact of climate change on soil organic carbon stock in upland soils in the 21st century in China. Agriculture, ecosystems & environment, 141(1-2), 23-31.

Wang, G., Zhang, W., Sun, W., Li, T., and Han, P. (2017). Modeling soil organic carbon dynamics and their driving factors in the main global cereal cropping systems. Atmospheric Chemistry and Physics, 17(19), 11849-11859.

Wang, Z., Zhang, B., Song, K., Liu, D., Ren, C., Zhang, S., Hu, L., Yang, H., and Liu, Z. (2009). Landscape and Land-Use Effects on the Spatial Variation of Soil Chemical Properties. Communications in Soil Science and Plant Analysis, 40(15–16), 2389–2412.

Wasonga, C., Sigunga, D., and Musandu, A. (2010). Phosphorus requirements by maize varieties in different soil types of Western Kenya. African Crop Science Journal, 16(2).

Waswa, B. S., Mugendi, D. N., Vanlauwe, B., and Kung'u, J. (2007). Changes in soil organic matter as influenced by organic residue management regimes in selected experiments in Kenya. In Advances in integrated soil fertility management in sub-Saharan Africa: challenges and opportunities (pp. 457-470). Springer, Dordrecht.

Waswa, Boaz S., Vlek, P. L. G., Tamene, L. D., Okoth, P., Mbakaya, D., and Zingore, S. (2013). Evaluating indicators of land degradation in smallholder farming systems of western Kenya. Geoderma, 195–196, 192–200.

Waswa, B. S. (2012). Assessment of land degradation patterns in western Kenya: Implications for restoration and rehabilitation (Doctoral dissertation, Universitäts-und Landesbibliothek Bonn).

Were, K., Bui, D. T., Dick, Ø. B., and Singh, B. R. (2015). A comparative assessment of support vector regression, artificial neural networks, and random forests for predicting and mapping soil organic carbon stocks across an Afromontane landscape. Ecological Indicators, *52*, 394-403.

Winowiecki, L., Vågen, T. G., and Huising, J. (2014). Effects of land cover on ecosystem services in Tanzania: A spatial assessment of soil organic carbon. Geoderma, *263*, 274–283.

Woomer, P. L., and Mukhwana, E. J. (2004). Working with smallholder farmers to improve maize production and marketing in western Kenya. Uganda Journal of Agricultural Sciences, 9(1), 491-500.

Yigini, Y., and Panagos, P. (2016). Assessment of soil organic carbon stocks under future climate and land cover changes in Europe. Science of the Total Environment, 557–558, 838–850.

Zhanbin, L., Qinling, Z., and Peng, L. (2013). Distribution characteristics of available trace elements in soil from a reclaimed land in a mining area of north Shaanxi, China. International Soil and Water Conservation Research, 1(1), 65-75.

Zhang, S., Li, Z., and Yang, X. (2015). Effects of Long-Term Inorganic and Organic Fertilization on Soil Micronutrient Status. Communications in Soil Science and Plant Analysis, 46(14), 1778–1790.

Zhao, Q., Tang, J., Li, Z., Yang, W., and Duan, Y. (2018). The influence of soil physico-Chemical properties and enzyme activities on soil quality of saline-alkali agroecosystems in western Jilin Province, China. Sustainability, 10(5), 1529.

Zheng, H., Liu, W., Zheng, J., Luo, Y., Li, R., Wang, H., and Qi, H. (2018). Effect of long-term tillage on soil aggregates and aggregate-associated carbon in black soil of northeast China. PLoS ONE, 13(6), 1–18.

Zhong, Z., Han, X., Xu, Y., Zhang, W., Fu, S., Liu, W., and Ren, G. (2019). Effects of land use change on organic carbon dynamics associated with soil aggregate fractions on the Loess Plateau, China. Land Degradation and Development, 30(9), 1070–1082.

Zomer, R. J., Bossio, D. A., Sommer, R., and Verchot, L. V. (2017). Global Sequestration Potential of Increased Organic Carbon in Cropland Soils. Scientific Reports, 7(1), 1–8.

APPENDICES

Appendix 1: Questionnaire used to identify the predominant management practices in the study sites

HOUSEHOLD SURVEY QUESTIONNAIRE

INTRODUCTION

The Department of Land Resource Management and Agricultural Technology, University of Nairobi in collaboration with CIAT are conducting research on the influence of agricultural management practices on soil organic carbon in Western Kenya, Vihiga and Kakamega Counties.

This questionnaire is meant to collect data on the adopted agronomic management practices biophysical and socio-economic factors among smallholder systems. The respondents for this survey shall be the main decision makers regarding production and other agricultural activities in the household who must be at least 18 years old. Information obtained is strictly for academic and research purposes only and responses obtained will be treated with confidentiality.

I would like to request your permission and time to carry on with this interview, which will last approximately15-30 minutes. Participation in this survey is voluntary we will respect your right if there are questions you would prefer not to answer. Your participation will be highly appreciated.

Are you willing to proceed with the interview?

YES ☐

NO ☐

Section 1: General information

HHID [_________________]

Date [____/______/_____] (*Date/Month/Year)*

1.1 County [________________]

1.2 Sub-county [________________]

1.3 Location [________________]

1.4 Sub-location [________________]

1.5 Village name [________________]

GPS coordinates:
Latitude [______________] Longitude [______________]

Altitude [______________]

Section 2: Household characteristics

2.1 Name of the respondent [_____________ __________________]

2.2 Age of respondent [________________]

2.3 Level of education [_________] 1= None 2=Primary, 2=Secondary 3=Tertiary

2.4 Gender [________________] 1=Female, 2= Male

2.5 Is the respondent the household head 0=No, Yes=1
If No, what is the relationship of the respondent to the household head [________] *use codes*
Codes: 1-husband/wife, 2-son/ daughter, 3-son/daughter in law, 4-father/mother, 5-grandchild, 6-sibling, 7-permanently employed worker, 991-other, *Specify [____________]*

2.6 Phone number [________________]

Section 3: Plot information

3.1 History of the land use for the last 3 years (***Indicate part of the plot where the practice is implemented).***

Management technologies	**1=Yes, 2=No**	

Tillage		
Manure		
Crop type		
Chemical fertilizer		
Crop rotation		
Agroforestry		
Crop residue management		
Herbicides		

3.1 Slope of the landscape [________________] 1=flat, 2=gently sloping, 3= steep

3.2 Erosion [________________] 1=none, 2=slight, 3=severe

3.3 Major crop grown [________________] 1=maize, 2=beans, 3=tea, 4=vegetable, 5=others, specify

3.4 Emergence rate of the crop [________________] 1=poor, 2=good

3.5 Livestock ownership [________________] 1=Yes, 2=No

Section 4: Fertilizer Inputs

4.1 Did you use inorganic fertilizer? [________________] 0=Yes, 1=No

If no, give a reason fertilizer

4.2 Type of inorganic fertilizer you applied [________________] 1= DAP, 2=Urea, 3= CAN, 4= others, specify

4.3 What was the quantity of fertilizer applied (kg)? [________________]

4.4 What was the method of application [________________] 1=broadcasting, 2=incorporated, 3=sub-soil placement

4.5 When was the time of fertilizer application [________________] 1=during land preparation, 2=planting, 3=crop emergence, 4=others (specify)

4.6 Where did you get the inorganic fertilizer? [________________] 1=Agro vet, 2=Neighbors, 3=Extension officer, 4=NGO, 5=One Acre Fund, 6=others, specify

4.7 Did you use organic fertilizer? [________________] 1=Yes, 2=No

If you no, give a reason

4.9 Which type of inorganic fertilizer did you use? [________________] 1=livestock manure, 2=chicken manure, 3=compost manure, 4=mixture of livestock, chicken and compost, 5=others, specify

4.10 State quantity of application (kg) [________________]

4.11 When was the time of application? [________________] 1=during land preparation, 2=planting, 3=crop emergence, 4=others, specify

4.12 Where did you get the organic fertilizer? [________________] 1= On-farm production, 2=buying, 3=neighbors, 4= others, specify

Section 5: Crop residue management

5.1 How do you manage crop residues for the major crops grown?

CROP 1

Crop	**Area of the land**	**Season 1**	**Season 2**

Crop residue	**Use (1= yes 0=No)**	**Proportion for season 1**	**proportion for season 2**
removed residue and designated for beneficial use e.g. fodder			
removed from field and disposed			
fuel			
grazed in situ			
Remains in the field as dead standing residue			
Remain in the field as surface residues			

Burned in situ			
Building material			
Fuel			
Others, specify			

CROP 2

Crop	**Area of the land**	**Seson1**	**Season 2**

Crop Residue	**Use (1= yes 0=No)**	**Proportion for season 1**	**proportion for season 2**
removed residue and designated for beneficial use e.g. fodder			
removed from field and disposed			
fuel			
grazed in situ			
Remains in the field as dead standing residue			
Remain in the field as surface residues			
Burned in situ			
Building material			
Fuel			
Others, specify			

CROP 3

Crop	**Area of the land**	**Season 1**	**Season 2**

Crop Residue	**Use (1= yes 0=No)**	**Proportion for season 1**	**proportion for season 2**
removed residue and designated for beneficial use e.g. fodder			
removed from field and disposed			
fuel			
grazed in situ			
Remains in the field as dead standing residue			
Remain in the field as surface residues			
Burned in situ			
Building material			
Fuel			
Others, specify			

CROP 4

Crop	**Area of the land**	**Season 1**	**Season 2**

Crop Residue	**Use (1= yes 0=No)**	**Proportion for season 1**	**proportion for season 2**
removed residue and designated for beneficial use e.g. fodder			
removed from field and disposed			
fuel			
grazed in situ			
Remains in the field as dead standing residue			
Remain in the field as surface residues			
Burned in situ			
Building material			

Fuel			
Others, specify			

Section 6: Tillage

6.1 Which are the tillage practices involved? [________________] 1=conservation tillage, 2=minimum tillage, 3=conventional tillage, 4=Agroforestry, 5= Intercropping, 6=Terracing

6.2 Tillage method used [________________] 1=hand hoeing, 2=Animal traction, 3=tractor, 4=others, specify

6.3 Time of land preparation [________________] 1=immediately after harvesting,2=2months before onset of rains,3=1month to onset of rains,4=at the onset of rain,5=1 week after the onset of rain,6=2 weeks after the onset of rain,7=1 month after the onset of rain

Section 7: Soil and water conservation measures

7.1 Which erosion control measures do you have in place? [________________] 0=none, 1=planting of trees, 2=Trenches, 3=Grass strips, 4=cover crops, 5= ploughing along contours, 6=stone lines, 7=gabions, 8=others, specify

Thank you very much for your time.

APPENDIX 2: Analysis of Variance (ANOVA) table for the effects of management practices on SOC stocks, total carbon and CN ratio down the depth

Table 1: ANOVA table for effect of chemical fertilizer on total carbon down the depth in Shikomoli

```
Response: Total Carbon
            Sum Sq Df F value    Pr(>F)
(Intercept) 4.0087  1 67.5081 2.858e-06 ***
DEPTH       0.0935  2  0.7876    0.4771
Residuals   0.7126 12
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 2: ANOVA table for effect of chemical fertilizer on SOC stocks down the depth in Shikomoli

```
Response: SOC stocks
            Sum Sq Df F value    Pr(>F)
(Intercept) 3789.0  1 64.1843 3.705e-06 ***
DEPTH         55.7  2  0.4719    0.6349
Residuals    708.4 12
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 3: ANOVA table for effect of chemical fertilizer on CN ratio down the depth in Shikomoli

```
Response: CN ratio
            Sum Sq Df   F value    Pr(>F)
(Intercept) 519.53  1 1321.1265 1.205e-13 ***
DEPTH         1.55  2    1.9757    0.1813
Residuals     4.72 12
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 4: ANOVA tables for effect of manure in combination with chemical fertilizer on SOC stocks down the depth Shikomoli

```
Response: SOC stocks
            Sum Sq Df  F value Pr(>F)
(Intercept) 9814.3  1 290.2016 <2e-16 ***
DEPTH         78.7  2   1.1629 0.3212
Residuals   1623.3 48
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5: ANOVA tables for effect of manure in combination with chemical fertilizer on total carbon down the depth in Shikomoli

```
Response: Total Carbon
            Sum Sq Df  F value Pr(>F)
(Intercept) 10.3553  1 276.2507 <2e-16 ***
DEPTH        0.1193  2   1.5914 0.2142
Residuals    1.7993 48
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 6: ANOVA tables for effect of manure in combination with chemical fertilizer on CN ratio down the depth in Shikomoli

```
Response: CN ratio
            Sum Sq Df   F value  Pr(>F)
(Intercept) 1915.91  1 3227.7674 < 2e-16 ***
DEPTH          4.91  2    4.1323 0.02209 *
Residuals     28.49 48
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 7: ANOVA tables for effect of manure in combination with chemical fertilizer and crop residue retention on SOC stocks down the depth in Shikomoli

```
Response: SOC stocks
           Sum Sq Df  F value    Pr(>F)
(Intercept) 8531.3  1 304.6939 5.593e-14 ***
DEPTH        208.1  2   3.7156   0.04154 *
Residuals    588.0 21
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 8: ANOVA tables for effect of manure in combination with chemical fertilizer and crop residue retention on total carbon down the depth in Shikomoli

```
Response: Total Carbon
            Sum Sq Df  F value    Pr(>F)
(Intercept) 10.0330  1 238.5916 6.104e-13 ***
DEPTH        0.4083  2   4.8546   0.01849 *
Residuals    0.8831 21
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 9: ANOVA tables for effect of manure in combination with chemical fertilizer and crop residue retention on CN ratio down the depth in Shikomoli

```
Response: CN ratio
            Sum Sq Df  F value Pr(>F)
(Intercept) 959.83  1 953.4750 <2e-16 ***
DEPTH         1.57  2   0.7777 0.4723
Residuals    21.14 21
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 10: ANOVA table for effect of chemical fertilizer on SOC stocks in Mukuyu

```
Response: SOC stocks
             Sum Sq Df  F value    Pr(>F)
(Intercept) 15347.8  1 500.8260 < 2.2e-16 ***
DEPTH         418.4  2   6.8267  0.003987 **
Residuals     827.4 27
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 11: ANOVA table for effect of chemical fertilizer on total carbon in Mukuyu

```
Response: Total Carbon
             Sum Sq Df  F value    Pr(>F)
(Intercept) 18.3630  1 492.0836 < 2.2e-16 ***
DEPTH        0.6240  2   8.3606  0.001493 **
Residuals    1.0076 27
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 12: ANOVA table for effect of chemical fertilizer on CN ratio in Mukuyu

```
Response: CN ratio
             Sum Sq Df  F value Pr(>F)
(Intercept) 1544.01  1 1586.744 <2e-16 ***
DEPTH          3.43  2    1.761  0.191
Residuals     26.27 27
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 13: ANOVA table for effect of combination of chemical fertilizer and crop residue retention on SOC stocks in Mukuyu

```
Response: SOC stocks
            Sum Sq Df  F value    Pr(>F)
(Intercept) 6515.5  1 199.0704 7.811e-09 ***
DEPTH        173.4  2   2.6484    0.1115
Residuals    392.8 12
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Table 14: ANOVA table for effect of combination of chemical fertilizer and crop residue retention on total carbon in Mukuyu

```
Response: Total Carbon
            Sum Sq Df  F value    Pr(>F)
(Intercept) 7.8150  1 263.2392 1.579e-09 ***
DEPTH       0.2663  2   4.4857    0.0351 *
Residuals   0.3563 12
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Table 15: ANOVA table for effect of combination of chemical fertilizer and crop residue retention on CN ratio in Mukuyu

```
Response: CN ratio
            Sum Sq Df F value    Pr(>F)
(Intercept) 757.68  1 703.794 5.044e-12 ***
DEPTH         0.90  2   0.418    0.6676
Residuals    12.92 12
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Table 16: ANOVA table for effect of combination of chemical fertilizer, manure and crop residue retention on SOC stocks in Mukuyu

```
Response: SOC stocks
            Sum Sq Df F value    Pr(>F)
(Intercept) 7839.7  1 92.7178 7.182e-05 ***
DEPTH        518.9  2  3.0683    0.1208
Residuals    507.3  6
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Table 17: ANOVA table for effect of combination of chemical fertilizer, manure and crop residue retention on total carbon in Mukuyu

```
Response: Total Carbon
             Sum Sq Df F value   Pr(>F)
(Intercept) 12.1082  1 21.3606 0.003609 **
DEPTH        0.9310  2  0.8212 0.483900
Residuals    3.4011  6
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 18: ANOVA table for effect of combination of chemical fertilizer, manure and crop residue retention on CN ratio in Mukuyu

```
Response: CN ratio
            Sum Sq Df F value    Pr(>F)
(Intercept) 489.01  1 685.713 2.046e-07 ***
DEPTH         0.55  2   0.388    0.6943
Residuals     4.28  6
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 19: ANOVA table for effect of combination of chemical fertilizer and manure on SOC stocks in Mukuyu

```
Response: SOC stocks
             Sum Sq Df  F value    Pr(>F)
(Intercept) 18786.4  1 420.3372 < 2.2e-16 ***
DEPTH         550.0  2   6.1527  0.005358 **
Residuals    1474.9 33
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 20: ANOVA table for effect of combination of chemical fertilizer and manure on total carbon in Mukuyu

```
Response: Total Carbon
             Sum Sq Df  F value    Pr(>F)
(Intercept) 24.8199  1 254.1400 < 2.2e-16 ***
DEPTH        1.2438  2   6.3679  0.004584 **
Residuals    3.2229 33
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 21: ANOVA table for effect of combination of chemical fertilizer and manure on CN ratio in Mukuyu

```
Response: CN ratio
            Sum Sq Df   F value Pr(>F)
(Intercept) 1875.05  1 1975.4435 <2e-16 ***
DEPTH          1.60  2    0.8419 0.4399
Residuals     31.32 33
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Appendix 3: Measured soil properties for all the farm

Farm	**DEPTH**	**Zn**	**Mn**	**Fe**	**Cu**	**Exch. Al**	**LM**	**SM**	**M**	**S+C**
		ppm	**ppm**	**ppm**	**ppm**	**ppm**	**%**	**%**	**%**	**%**
Farm 1	0-20	8.70	12.35	60.75	0.35	0.00	10.75	59.92	23.65	5.24
Farm 1	20-40	5.40	14.45	33.25	0.24	0.20	6.42	63.10	25.52	4.68
Farm 1	40-60	7.80	10.25	30.95	0.01	0.10	3.56	64.54	23.55	7.79
Farm 2	0-20	11.30	35.65	72.60	0.99	0.15	2.98	62.60	25.41	8.61
Farm 2	20-40	20.20	40.35	75.20	0.18	0.05	7.27	70.44	19.55	2.56
Farm 2	40-60	9.20	35.85	111.90	0.99	0.55	3.52	61.72	27.10	6.98
Farm 3	0-20	6.80	18.95	100.72	1.67	0.15	14.55	43.67	29.75	11.42
Farm 3	20-40	0.80	10.85	235.80	1.56	0.25	6.30	56.39	29.26	7.65
Farm 3	40-60	7.10	5.05	39.90	0.01	0.25	0.47	56.48	33.87	8.95
Farm 4	0-20	3.90	43.25	64.80	1.39	0.15	11.15	39.97	38.00	10.44
Farm 4	20-40	0.10	23.45	86.60	0.05	0.70	56.88	31.29	10.35	1.46
Farm 4	40-60	0.60	8.75	39.20	0.78	0.90	55.61	32.99	9.85	1.43
Farm 5	0-20	6.20	78.15	65.92	1.56	0.15	8.49	37.79	43.66	8.87
Farm 5	20-40	5.20	61.65	71.92	1.94	0.20	13.41	44.53	35.43	5.80
Farm 5	40-60	3.60	40.95	208.80	2.01	0.10	13.18	39.20	39.75	7.19
Farm 6	0-20	2.20	16.25	6.30	0.07	0.75	3.96	50.16	35.87	9.23
Farm 6	20-40	2.30	8.75	0.90	0.00	0.25	13.19	68.24	15.99	2.25
Farm 6	40-60	2.60	11.65	0.70	0.22	0.40	8.03	69.09	19.18	3.40

Zn- Zinc, Mn- manganese, Fe- iron, Cu- copper, Exch. Al- exchangeable aluminium, LM- large macro-aggregates (≥ 2 mm), SM- small macro-aggregates (≥ 250 µm ≤ 2 mm), M- micro-aggregates (≥ 53 µm ≤ 250 µm), S+C- silt plus clay ((≥ 53 µm)