EFFECTS OF LAND USE AND LAND COVER TYPES ON SOIL ORGANIC CARBON STOCKS AND SOIL LOSS DUE TO GULLY EROSION IN OLESHARO CATCHMENT, NAROK COUNTY, KENYA

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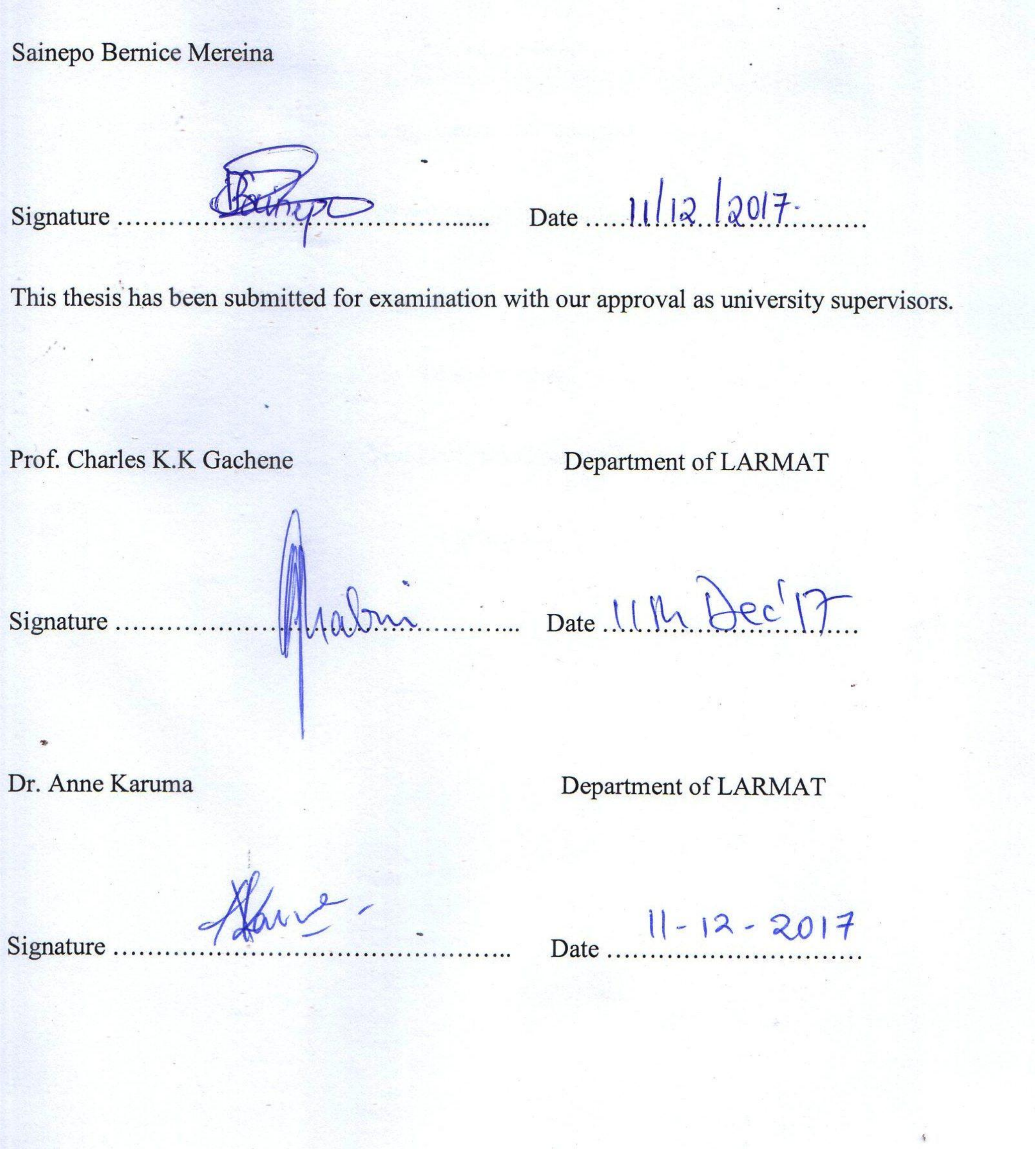
Thesis submitted in partial fulfilment for the requirements of the degree of Master of Science in Soil Science, Department of Land Resource Management and Agricultural Technology, University of Nairobi

DECLARATION

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



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DEDICATION

To my mentor, Pastor Judah Kalinga,

You showed me I could dream big,

‘*You’re my light’*

To my Father, Mr Sainepo

For not accepting excuses

Thank you.

To my mother,

You have raised me well

I love you.

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I am grateful for the technical support I received from Mr Ferdinand Anyika, Mr John Kimotho and Mr Boniface Muliro, for the countless hours you helped me with my samples, this degree is as much yours, as it is mine.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

ACZ: agro-climatical zones

ASALs: arid and semi-arid lands

CMI: Carbon management index

FAO: Food and agriculture organization

GEFSOC: Global Environment Facility Soil Organic Carbon

GOK: Government of Kenya

IPCC: Inter-governmental panel on climate change

LULCC: land use and land cover changes

LUTs: Land use types

MEA: Millennium ecosystem assessment

MOC: Mineral organic carbon

NPP: net primary productivity

PET: Potential evapotranspiration

POC: Particulate organic carbon

SOC: soil organic carbon

SOM: soil organic matter

TOC: Total organic carbon

UNEP: United Nations environmental programme

FOREWORD

The chapters in this thesis are structured as papers and have been submitted to peer-review journals. I would like to apologize to the reader for the inconvenience caused by the repetition of some sections dictated by this mode of presentation.

ABSTRACT

Land use and land cover changes have posed serious effects on the ecosystem particularly on soil quality and sustainability. This study sought to investigate effects of land use and land cover changes on soil organic carbon (SOC) within the southern ASALs of Kenya. The specific objectives of this study were to evaluate the effects of different land use/ cover types on soil organic carbon stocks (SOCst) and total nitrogen stocks (TNst) in the Olesharo Catchment, Narok County; to assess impact of different LUTs on carbon fractions and carbon management index; and to determine the total carbon and sediment lost from the gully. Using LandSat imageries, four land use types were identified: shrubland (SH), agricultural land (AG), grasslands (GR) and barelands (BL). Disturbed and undisturbed soil samples were taken from 30 x 30 m plots randomly distributed for each of the LUT at 0-15 cm and 15-30 cm depths for the analysis of SOC/ and TN stocks. Similar procedure was taken for the carbon fractions to analyse for total organic carbon (TOC), particulate organic carbon (POC), and mineral organic carbon (MOC). Further, the carbon management index (CMI) for each land use type was calculated using shrublands as the reference land use. For total SOC lost from the gully channel, profile pits were dug adjacent to each channel and undisturbed samples collected from each identified horizon. Dimensions of the channels of the gullies were used to calculate the total sediment lost. The study showed that the means of SOC in land use types were significantly different ($P < 0.05$). Shrublands registered the highest mean total of SOCst of 31.26 Mg C ha^{-1} while bareland was the least with 12.85 Mg C ha^{-1} which were significantly different from each other. Grasslands unexpectedly had significantly lower SOCst compared to AG and this could be attributed to overgrazing in the catchment. Similarly TN stock registered the same results as SOC stock which was validated by corresponding C/N ratios. For carbon fractions, POC was the most sensitive pool, indicating that it can be used as an early indicator for soil degradation. Shrubland had significantly higher ($p < 0.05$) POC at 7.79 g kg^{-1} and lower in GR and BL at $P < 0.05$. The CMI showed that level of degradation in the GR was as severe as that of BL. Therefore efforts aimed at improving SOM within each land use types will improve the soil quality and otherwise reverse degradation within the catchment. The total amount of sediment lost from the gully was high at 313748.71 tons of soil obtained from the gully dimensions. The study further showed that in the sediment area, the SOC recorded was lower in the upper horizons and higher in the lower horizons. This may be due to burial of SOC rich top soils by low carbon sub-layers which purports that erosion is a carbon sink as opposed to a source. Overall the study concluded there is need to improve grazing management strategies in the catchment and it also highlighted the possible climate change mitigation strategies by sustainable management of different land use types.

Key words: carbon stocks, carbon fractions, total sediment loss, land use/ land cover change, Olesharo Catchment

CHAPTER ONE

1.0 Introduction

1.1 Background Information

Soil organic carbon (SOC) plays a vital role within the overall carbon cycle (Van Oost *et al*., 2007). Central to the present concept; soil sequesters averagely three hundred times of carbon created by industrial burning of fossil fuels (Lal, 2005; Schulze and Freibauer, 2005). So any slight changes to SOC can have a negative effect on provision of system services. Being preferentially found on the surface, SOC has comparatively lower density, making it easier for it to be carried off by runoff (Kimble *et al*. 2001). Several studies have shown that the typical loss of SOC by water erosion annually is 1-5 Pentagramme of carbon that is consequently deposited at the lower areas of a catchment (Berhe, 2012).

Soil organic carbon (SOC) includes organic compounds (i.e., plant, animal and microbial residues in any stage of decay) that are highly enriched in carbon (Lal, 2008). Consequently the role of SOC is important in edaphic factors like physical properties, chemical and biological factors of the soil (Kwon *et al*, 2000; Ardo and Olsson, 2002; Rice, 2005). Soil carbon is affected on a spatial and temporal scale by climatical, edaphic, biotic and lithological factors which influence the balance between the gains and losses of soil carbon (Kurgat, 2011). However, most of the carbon fluxes between the atmosphere and the Earth’s surface are attributed to anthropogenic factors, primarily land use and land cover changes (IPCC 2013).

Land use is one of the major causes of soil erosion and consequent loss of soil organic carbon in the ecosystem (Nie *et al*, 2013). Moreover, land use changes has been recorded to be the second largest source of anthropogenic source of green-house gases accounting for 12-20 %

of carbon emissions (IPCC, 2007). Land use change has become prevalent in the sub Saharan Africa and more specifically Kenya with the drivers being socio-economic as well as political gears (Government of Kenya 2009; UNEP 2009; Serneels, 2001). The most prominent types of conversions in tropical soils are from forest and grasslands to agricultural lands (FAO, 2006) with estimates of about 0.2 Gt C yr^{-1}. Soil carbon is primarily influenced by plant production through presence of micro-climates, litter quality and carbon pathways. These factors affect rates of decomposition which influence nutrient availability for plant uptake and carbon emissions released to the air (Kindermann *et al*,. 2008).

A study in New Zealand has shown that conversions from prevailing land use types to new ones has led to a distinctive loss of SOC by 9.5% in the grasslands (Davis and Condron, 2002). In addition, studies in Northern Great Plains have indicated that different forms of carbon can be used as an indicator of sustainable land use types (Aguilar *et al.,* 1988*)*, While Nyawade *et al*., (2016) exemplified that erosion under different potato cropping systems has an impact on different SOC fractions.

Land use change is second to none as a lead cause of land degradation in which soil erosion is the most severe form (Oldeman, 1997; Jobaggy and Jackson, 2000; Lal, 2002). Pimentel, (2006) articulated that loss of soil from land surfaces due to erosion is widespread globally and adversely affects the productivity of all natural systems as well as agricultural, forest and range lands. Globally, land degraded due to erosion by water is 1064 million hectares, of which 751million ha is severely affected (Lal, 2002). In Africa, for instance about 5 Megagrammes per ha of productive topsoil is lost to lakes and oceans each year (Angima, 2003).

Soil that has been degraded has poor structure, which can be attributed to low surface soil organic matter (SOM). Land degradation in rangelands is characterized by loss of perennial plant cover and visible pockets of bareland across the land scape (Tongway and Ludwig, 2011; Bestelmeyer *et al*., 2015). In the Drylands, soil erosion has severe *in- situ* and *ex-situ* effects such as removal of top valuable soil which leads to loss of net primary productivity of the ecosystem. Moreover erosion drastically influences the soil chemical properties which deteriorate the overall soil fertility of the area, one such characteristic is soil organic carbon (SOC) loss (in this study, SOM and SOC will be used interchangeably).

The dynamism of SOC in different land use is a popular subject in different researches; (Demessie *et al*., 2013; Awiti *et al*. 2008; Solomon *et al*. 2000). However, studies done on the impact of land use change and intense erosion on SOC is still scarce, therefore the potential role of SOC in climate mitigation is still an avenue for exploration. There has been a great debate on whether soil erosion is a source or a sink of SOC. During detachment of the erosion process, the macro aggregates are broken down exposing the SOM to decomposition and release of carbon dioxide (CO2). At the sedimentation area, the SOC is buried deep within soil profiles of high bulk density, low total porosity, and small pore sizes impeding access by decomposers and their enzymes therefore not readily mineralized (Berhe, 2012). Such studies (Stallard, 1998; Smith *et al*., 2001; Renwick, 2004) support the school of thought that erosion is a sink while others purport that erosion increases mineralization therefore acting as a source of carbon loss (Lal, 2003; Lal *et al*., 2004a).

Global concerns over the changes in land use/cover have emerged due to realization that land surface processes influence climate and that change in these processes impact on ecosystem goods and services (Lambin *et al*., 2003). The link between land use change and erosion has particularly gain interest in the Olesharo Catchment as a consequent of the gully network that is a threat to lands used for grazing and agriculture, water resources and road networks.

1.2 Statement of the problem

Land degradation in ASALs is a potential precursor to widespread desertification and is linked to various human induced factors as a result of land use change and poor management practices. Drylands are undergoing land use and land cover changes especially to croplands and human settlement. This is attributed to increased human population and the need to diversify income livelihoods (Tsegaye *et al*., 2012). There are visible repercussions of decades of land use changes which have caused erosion within the Olesharo catchment; unsustainable farming practices, curtailed livestock mobility and over-exploitation of available pastures, encroaching on wet- season grazing areas for pastoralists as well as encroachment of agriculture into marginal land (Odini *et al*, 2015).

The exacerbation of soil erosion is attributed to poor soil qualities, like low SOC among others. Moreover with the accelerated loss of soil, there is severe loss of SOC from the surface and subsurface soil noting that even slight changes in the SOC pool can significantly affect the global carbon cycle (Powlson *et al*. 2011). This impedes carbon sequestration potential as well as uneven lateral distribution of SOC stocks which affect soil quality within the catchment. Therefore, there is a need to better understand the effect of land use on SOC dynamics within the drylands and how this can be harnessed in soil water conservation techniques as well as climate change mitigation.

1.3 Justification

The need to mitigate loss of top soil has gain prominence in the drylands. Several strategies have been employed within the catchment under the Sustainable Land Management (SLM) initiative to control erosion through physical control measures. However, there is still a need of ways to inherently conserve the soil through deeper understanding of its chemical properties. Research shows that the conservation of SOC in soil improves its physical properties like particle aggregation and cohesion within the structure which reduces erosion.

This study will attempt to understand how land use/ cover changes and gully erosion affect soil organic carbon stocks and carbon fractions within the soil. Consequently, assessing which types of land use/land cover type are sustainable within the catchment by evaluating each land use' carbon management index (CMI).

The role of below ground biomass in carbon sequestration has become popular especially with the need to reduce the levels of CO2 within the atmosphere (CoP, 2015). In addition, management of SOC in different types of land use/ cover types has been highlighted as a potential strategy in the adaptations to climate change. Therefore results from this study is expected to add empirical evidence to the role of sustainable land use management in soil water conservation and climate change adaptation.

Plate 1.0: Gully at mid-slope

Plate 2.0: Gully head

1.4 Research objectives

1.4.1 Broad objective

To assess the effects of land use/ land cover types on soil organic carbon stocks and soil loss due to gully erosion in Olesharo catchment, Suswa.

1.4.2 Specific objective

1. To assess total SOC stock under different LU types in the Olesharo catchment.
2. To assess the relative proportions of SOM fractions that are more vulnerable to changes due to changes / conversion in LU
3. To determine total SOC loss and total sediment loss due to gully erosion in Olesharo catchment.

1.5 Hypothesis

1. There is no significant variation in SOC and Total nitrogen (TN) stocks under different land use types
2. The labile SOM fraction is not prone to soil erosion
3. The total soil and SOC loss from the gullies are within tolerable limits.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Land use and land cover changes

There are many different aspects and definitions relating to land use. According to Lambin (2006) and Lillesand (2008) land cover refers to the characteristics of the Earth's surface and direct subsurface, for example biota, soil, topography, surface and groundwater and human structures (mainly built-up structures). The pressure exerted on land today to support rapid population growth has led to degradation of land. This degeneration has become a longstanding and increasingly severe problem in most tropical countries, especially sub-Saharan Africa (Muniya and Aniya, 2006; Kiage *et al.*, 2007; Ries, 2010). Poor and inappropriate land management practices result in rapid land degradation, massive soil loss, falling crop yields, deforestation, the disruption of water resources and the destruction of natural pastures (Nabhan *et al.*, 1999). Foley, (2005) compounded that land use and cover changes from native entities to production ventures has and will lead to a threat in environmental functionalities.

Land use changes in East Africa have transformed land cover to farmlands, grazing lands, human settlements and urban centres at the expense of natural vegetation. These changes are associated with deforestation, biodiversity loss and land degradation (Maitima and Mugatha, 2009). Kenya's Arid and Semi-arid areas are about 467,200 square kilometres or about 80% (and increasing) of the country's total landmass and are characterized by generally hot and dry climate, low and erratic rainfall patterns makes the land most suitable for livestock production compared to other land use types (Miriti *et al.*, 2012). Consequently, over the years, there have been changes in land use systems that have resulted in severe land and natural resources degradation. The impacts that have been of primary concern are the effects of land use change on biological diversity, soil degradation and the ability of biological systems to support human needs. Crop yields have declined, forcing people to cultivate more and more land to meet their needs (Kaihura and Stocking, 2003) which has been seen to have severe detrimental consequences to land.

According to Khalif *et al.*, (2015), the Kenyan ASALs are in a critical stage in land use change. Nearly all our needs; wood for fuel and shelter, food, water and other products come from the land and renewable resources on it. This reality is paramount for Kenya whose land is the most strategic resource and natural capital that form the backbone of the country's subsistence and national economies. These drylands support millions of pastoralists and more so livestock and wildlife (Mganga, 2011). Therefore any slight changes to the land cover mosaic can have serious detrimental impacts on the countrys' food security, socio-economic problems and the regions' large mammalian wildlife diversity (Matano *et al*., 2015; Kimiti *et al*., 2016).

Much of Suswa area, Narok is in transition from pastoralism to agro-pastoralism (Maina, 2013). In the Olesharo catchment, previous communal land has been sub-divided and fenced hence livestock movements are restricted (Ruto, 2015). The highlands are characterised by large plantations of wheat and barley, while the lowlands are dominated by sheep, goats and small herds of cattle, punctuated with cultivated patches. As is common in drier areas, 60% of the carbon is below ground biomass (Woomer *et al*., 1998). This is especially important as land use and land use change affects drastically soil quality. However it should be noted that not all the forms of carbon are easily affected by land use, some can last up to 100 years while some change per season (Lal, 2010).

2.2 Effects of Land use/cover change on SOC and TN

Carbon inputs to the soil are largely determined by the land use; with forest systems tending to have the largest input of C to the soil (inputs all year round) and often this material is also the most recalcitrant (Bolin and Sukumar, 2000). Grasslands also tend to have large inputs though the material is often less recalcitrant than forest litter and the smallest input of C is often found in croplands which have inputs only when there is a crop growing and where the C inputs are among the most labile (Smith, 2008). The rate of C input to the soil is related to the productivity of the vegetation growing on that soil, measured by net primary production (NPP). The NPP varies with climate, land cover, species composition and soil type (Sharma *et al.,* 2012).

A study done by Were *et al*. (2015), on the effects of land use conversions on SOC showed that there was a distinct loss of concentration and stock of soil carbon from natural forest to crop lands. This study indicated that transformation from natural to human-dominated landscape increases the risk of soil degradation and restricts the ecosystem's capacity to store carbon and nitrogen. Similarly, Post and Kwon, (2002) validated that a conversion from cropland to grassland would also increase the carbon stock in the soil, or an intercrop crop and permanent grasses. Different studies have examined the effects of land use/ cover change on soil physio-chemical properties, and most concur that despite its consequences, land use change frequently leads to nutrient losses and reduction of organic matter inputs in the soil.

Conversion of natural forest to other forms of land uses such as; farmlands and pasturelands have been seen to lead to soil erosion and subsequent reduction in soil nutrients and modification of soil structure (Guo and Gilfford, 2002; Schulp *et al*., 2008). Conant *et al*., 2001 illustrated that there is a 9% SOC loss from a shift of land use from grasslands to croplands. While a research done in China (Li *et al*., 2013) reported that there was a general decrease of 13.62% in SOC from natural vegetation to farmland in the oasis of Sangong river watershed. Some researchers have however shown different results. A case study done by Neil and Davidson (2000) showed that there was a 45-56% increase of SOC in the amazon forest Brazil from forest land to grassland for pastures of up to 7 years old. This shows that different land cover types have different effects on soil organic carbon and with proper management, can cause increase of soil quality.

Some land use changes negatively affect soil productivity characteristics such as soil bulk density and hydraulic conductivity (Islam and Weil, 2000). Cultivation of forests for instance can diminish SOC within a few years of initial conversion (Murty *et al*., 2002), and substantially lower mineralizable nitrogen (N) (Ritcher, 2000). In conversion, Noellemeyer *et al*. (2008) recorded that the soil can lose about 16% of its original SOC and double its loss in the second year of cultivation. Emadi *et al*. (2008) in Iran recorded similar findings. The results showed that a conversion from natural pasture to croplands increased soil bulk density by 16% and increased general soil erodibility by 51%. Moreover it was illustrated that the soil lost up to 40% of its available water holding capacity for the 0-20 cm soil depth. A study done in the Nzoia river basin, western part of Kenya, showed that grasslands increase storage of SOC and a prominent source of carbon sink (Wabusya *et al*., 2015). Furthermore other studies indicated that only when the land is overgrazed is there depression of carbon, nitrogen, phosphorus and sulphur due to reduction of above ground biomass (Bardget and Wardle, 2003; DeDyn *et al*., 2008; Semmartin *et al*., 2010).

Herbivory is the primary factor in N- cycle in grasslands (Frank *et al*, 2004). This happens through, ingestion of grasses by cattle and wildlife and consequently excretion of faecal matter by the same. The high consumption rates of ungulates in the tropics plays a key role in the N deposition through patches of urine in which nitrogen is easily volatilized (Hobbs, 1996; Frank *et al*., 1998). Several studies investigating the influence of anthropogenic activities on N volatilization (Ruess and McNaughton, 1998; Frank and Zhang, 1997) which have approximated N loss to range between 10 - 40 %. Changes in land use and cover expose soil to higher temperatures which increases conversion of organic N to NH_3 (Alphayo, 2015).

2.3 Land use/cover monitoring

The identification and monitoring of land use and land cover change has become an important thematic area of research due to the increasing change in climate and its impacts thereof to man (Asubonteng, 2007). The Digital change detection is done through determinative and/or describing changes in land-cover and land-use properties based on co-registered multi-temporal remote sensing information (Chan *et al*., 2001). The fundamental premise in the use of remote sensing information for change detection is that the method will determine change between two or more dates that's atypical of expected variation (Baldyga *et al*., 2008). These variations are caused by differences in radiance values that are more distinct from land cover types as compared to those caused by either soil moisture or atmospheric conditions (Mas, 1999).

Several methods do exist in change detection using satellite imagery. They include; image referencing, vegetation index differencing (NDVI), selective principal component analysis (SPCA) and direct and multi-date classification (Nelson 1983; Singh, 1989; Chavez and Kwarteng, 1989; ERDAS, 1991). Although no technique is full proof, processing of multi date classifications helps to show the rate of change and the nature of change which can be used to determine hotspots and therefore develop timely mitigation strategies (Baldyga *et al*., 2007). Through research, it is seen that landscape conversion can be monitored and documented. Although this is true, the dynamism of LULC changes makes it hard to find an ideal solution for all the problems associated with it. In the quest for understanding such problems, the application of Remote Sensing and GIS in collection, processing and interpretation of data in assessing the nature, magnitude and the rates of change has become of chief importance.

2.4 SOC in the Drylands

Dryland ecosystems are defined as regions in which the ratio of total annual precipitation to potential evapotranspiration (PET or the Aridity Index, AI) ranges from 0.05 to 0.65 (Dregne, 1983; Glenn *et al*., 1993, Reynolds and Smith, 2002). ASALs (which would be used interchangeably with Drylands in this study) are characterised by low erratic rainfall, subject to temporal and spatial variability. These fluctuations indicate that rainfall varies from 2000-500mm/yr which support crop growth and forages (Ruto, 2015). The net primary productivity in ASALs is relatively low, consequently low above ground biomass as well.

Kenya is predominately a dryland which covers up to more than 80% of the area (Mwang'ombe *et al*, 2011). This would mean that Kenya is highly dependent on the drylands to provide food, fibre and fuel for most of its people. The soils in the semi-arid areas are characterised by low soil moisture content, shallow with low SOM content (Nandwa, 2001). In addition, a study done by the Global environmental facility soil organic carbon (GEFSOC), reported that soil organic carbon is distributed sparingly within the agroclimatical zones. Batjes (2004) reported that SOC in Kenya ranges from 1896-2006 teragram (= 1 x 10^9 kilograms) C in the upper 30cm and 3452-3797 Tg C in the upper 100cm. The lowest registered SOC concentrations are in the AGZ VII which is approximately 0-18 t C ha^{-1}.

Table 2.1 Area-weighted content of organic per agroclimatic zone (ACZ) of Kenya

ACZ	Organic carbon (kg C m^{-2})		
	0–30cm	0–50cm	0–100cm
I	7.7–7.9	11.4–11.5	15.4–15.7
II	6.8–6.9	10.0–10.1	13.4–13.7
III	5.2–5.3	7.5–7.6	10.2–10.3
IV	4.6–4.7	6.6–6.7	8.7–8.8
V	3.6–3.7	5.1–5.2	6.8–6.9
VI	2.9–3.0	4.1–4.2	5.7–5.8
VII	2.2–2.3	3.2–3.3	4.4–4.5
All	3.2–3.3	4.6–4.7	6.3–6.4

ACZ; Agroclimatic zones. Sources: Batjes (2004).

2.5 SOC pools

Scientists have reported three pools of soil carbon depending on turnover rates. They include; labile pool, slow and the resistant pool (Haynes, 2005; Rice, 2005; Kurgat, 2011). Although this may be convenient, SOC contains carbon on a continuum process ranging from highly decomposable to very recalcitrant proving difficult to differentiate. The labile fraction has garnered a lot of interest because of its vulnerability to climate, geophysical processes and management practices (Kapkiyai, 1999; Jacinthe, 2001). Woomer *et al*. (1994) compounded that proper identification of labile fractions can be used as an indicator of soil quality subject to land management geared to conserve soil physical properties. Moreover, De Souza *et al*., (2015) reported that the labile fraction (LF) illustrates a better understanding of SOM to LULUC on a catchment scale compared to other carbon fractions.

The LF is found in the transition between fresh residues and stabilized fractions with a turnover period of less than 10 years (Allen *et al*., 2010). In the physical fractionation procedure, it is found between the sieves 250µ and 53µ (Camberdella and Elliot, 1992). Being of light density, this pool is found as a microaggregate in the hierarchical postulation of fractions based on their physical size (Detxter, 1988) through the wet sieving method.

The Stable Fraction (SF) has a turnover period of about 10-200 years. The reasons for this can be attributed to the mineral nature of the SOC. This makes it physically impossible for the carbon to be accessed by microorganisms and extracellular enzymes for breakdown (Allen *et al*., 2010). The adsorption of SOC on stable macroaggregates (<53µ) such as clay particles increases the mean residence time in the soil through formation of clay-SOC complexes (Rabbi *et al*., 2014). Due to its abundant presence of about 90% of the total SOM, some scientist think it's the most vulnerable to soil erosion (Cheng *et al*., 2013; Wang *et al*., 2013;Nyawade *et al*., 2016) since they have high densities making it easier to move with the surface water. In contrast, Jacinthe *et al*. (2004) showed that the LF was more prone to erosion due to the fact that at raindrop impact, the aggregates disperse releasing the light fractions and making it easy to be carried away by surface runoff.

2.6 SOC and Ecosystem services.

Soils and soil organic carbon particularly, receives a lot of attention in terms of the role they play in mitigating the results of elevated atmospheric carbon dioxide (CO2) and associated global warming. The fundamental construct of SOC is through the understanding of the carbon cycle (Parton *et al*., 1995; Lal, 2004; Davidson and Janssen, 2006). In terrestrial ecosystems the supply of soil organic carbon input is from photosynthesis or net primary productivity. Assimilates are transferred on to the roots via the vascular tissue or may be regenerated to biomass that may be transferred to the soil via litter. Carbon within the soil is found in two forms; organic and inorganic. In the organic type, there are 3 fractions that are discretionally classified for modelling purposes; fast, slow and passive indicating the speed of turnover (Rodeghiero *et al*., 2013). However, it's arduous to relate these pools to soil carbon fractions. Most of the soil organic carbon is not inert, rather it is in a continuous dynamic state of accumulation and decomposition (Janzen, 2004; Schrumpf *et al*., 2008)

SOC in the form of organic matter is a key component of the soil ecosystem structure, and is used as an indicator of ecosystem functionality (Conant *et al*., 2001). It contributes many flows and transformations of organic matter, energy and biodiversity, (Noellemeyer, 2014). These essential soil functions provide ecosystem services and life sustaining benefits from the soil. Some of the prominent ecosystem services include food production, water storage and infiltration, carbon storage, nutrient supply to plants, habitat and biodiversity (Noellemeyer *et al*., 2014; Lal, 2013). Drawing from the concept of ecosystem services within the millennium ecosystem assessment (MEA, 2005), soil carbon plays the roles of provisional, supporting and regulating services to the ecosystem.

SOM plays a central role to all underpinning physical, chemical and biological processes of soil functions. Soil carbon is associated with improvement of soil structure, reduced bulk density, plant productivity and wet conditions that ensure water supply to the soil. Consequently, soil structure is responsible for the formation of stable larger aggregates and larger inter-aggregate pores that create greater soil permeability and drainage for root growth (Baker *et al*., 2007; Schmidt *et al*., 2011). Smaller interior pores within aggregates, on the other hand, provide water holding capacity to sustain biological processes. Chemically, SOC is the basis of soil fertility (Six *et al*., 2006). SOM creates cation exchange sites and acting as reserve of plant nutrients, especially nitrogen (N), phosphorus (P), and sulphur (S), along with micronutrients which are slowly released upon SOM mineralization (Kapkiyai *et al*., 1998).

Within the soil, the microbial component also plays an important role in the ecosystem. These microbes and their population richness and diversity are directly proportional to the amount of soil carbon in the soil (Bationo, 2007). As a food source; increasing soil carbon provides carbon and energy to support microbial activity which plays an important role in the soil food web. This in turn regulates nutrient cycling and nutrients (Chan, 2008) available to the plant which assist root growth and control soil diseases. Even with the intense dependence of soil to sustain life, soil and soil carbon are still under threat worldwide due to resource demands, soil erosion and the increasing intensification of land use. In addition, SOC can lessen the effect of harmful substances for example toxins, and heavy metals, by acting as buffers, e.g. sorption of toxins and heavy metals, and increasing degradation of harmful pesticides (Beesley *et al*., 2010).

Soil has relatively high capacity to store carbon and a report done by Lal (2001), showed that the rate has been significantly reduced by increasing number of managed ecosystems, leading up to 50-70% loss of the original SOC pool. Moreover, the magnitude of SOC depletion is high in soils prone to erosion and those poorly managed by low input or extractive farming practices as well as detrimental grazing practices. According to research, the maximum soil carbon sink capacity equals the historic carbon loss (Smith, 2008; Lal, 2010). This translates to; most conversions from natural to managed ecosystems contain lower SOC pool than their capacity because of their historic loss. This maximum capacity is determined by the climate, parent material, physiography, drainage and soil properties which include clay content. Usually the SOC pool is at a dynamic equilibrium under any specific land use and management system. For soil to be considered sequestering then the C inputs should be more than the C outputs. When in a steady state, the C inputs are equal to the C outputs, while SOC is said to be depleted when the C inputs are less than the C outputs.

2.7 SOC and Climate change

Soils represent the largest terrestrial stock of carbon, holding approximately 1,500 Pg (1billion tonnes or 1g x 10 ^{15}) C in the top metre. This is approximately twice the amount held in the atmosphere and thrice the amount held in terrestrial vegetation (Lal, 2015). This implies that the soil has the capacity to sequester carbon and act as a sink, and transferring atmospheric CO2 into long-lived pools and storing it securely so it is not immediately reemitted. The potential impact on climate change has forcibly incentivised the world, and particularly Africa to develop strategies in dealing with greenhouse gases. The potential of semi-arid climates in acting as carbon sinks is great with studies showing that the SOC pool up to one meter depth is about 30tons/ha (Lal, 2004). A study done under the GEFSOC predicting the SOC of Kenya between 1990 to 2030 corroborates Lal's (2004) findings showing that the country registers averagely 18 - 30t C ha^{-1} (Kamoni *et al*., 2007).

The compounded conclusion of the research was that Kenya is predicted to lose about 104 Tg C by 2030 meaning that drastic measures must be taken to improve SOM levels within the soil. Carbon dioxide is the most prominent greenhouse gas in Kenya (Schlesinger, 2000), and so the ratification of the UNFCCC on 30th August 1994 saw her determination to join the international community in combating the issue of climate change (GoK, 2002). Kenya undertook an inventory of the greenhouse gas emissions in her jurisdiction and concluded that it is a net carbon dioxide sink absorbing approximately 22,751 Gt, CO2 per annum (GoK, 2002). According to reports done by the IPCC (2007); GoK (2009), there has been a temperature rise of 1°C over in the past 50 years and another 3°C by 2050. Like most African countries, Kenya is vulnerable to climate change and therefore the need to harness the potential of soil as a sink is a relevant gap in research to improve livelihoods. However such an anticipated C sink by the soil can only be achieved if land is well managed.

2.8 Soil erosion

Soil erosion is the most significant contributor of land degradation. About 85% of the earth's land degradation is as a result of soil erosion (Angima, 2003). According to literature, the global estimation of soil lost by erosion is up to 75 billion Mg yr^{-1}, (Pimentel *et al*., 2005). Global Assessment of Soil Degradation estimates that 65% of African agricultural lands, 31% of permanent pasture land, and 19% of forest and woodland is degraded (Muchena and Onduru, 2005). Lal (2010) reiterated the total land affected by water erosion covers up to 1094 Mha, of which 751Mha is severely affected. The report further mentions that water and wind erosion, respectively, account for 46% and 38% of total soil degradation in Africa.

The semi-arid regions of sub Saharan Africa are considered as regional hotspots for water erosion (Sherr and Yadav, 1996). With increasing interest of the externalities that result from gully erosion, global concern has developed over how to deal with this kind of erosion at a catchment level, (Valentin *et al*., 2005).

In Kenya, the challenge of soil erosion has become a concern over the last several decades. By the year 1935, the challenge had begun to be addressed (Ongwenyi *et al*., 1993). UNEP, (2004) published a report showing hotspot areas subject to severe erosion and listed affected semi-arid counties like; Machakos, Kwale, Kilifi, Kitui, Kajiado, Samburu, West Pokot, Narok, Laikipia, Baringo, Elgeyo Marakwet, and Marsabit. Gully erosion is a threshold triggered event. According to literature; (FAO, 1991; Nill *et al*., 1996; Lal, 2001; Smith *et al*., 2001), some of the salient causes of water erosion also include socio-economic; poverty, land tenure systems, livelihood practices, and institutional frameworks

In particular, and which is one of the main focus of this study, gully erosion in the catchment occurs predominantly in badlands or hilly regions (Valentin, 2004). Moreover, the gully process is triggered by several ecological factors that may include; soil properties, terrain characteristics, land cover and use, or climate of the area. According to work done previously by Konana *et al.* (2017) in the same area of study, the processed chronosequent Landsat imageries show that significant land cover changes have occurred within the catchment over the last three decades.

In the Olesharo catchment, the prominent soils are andosols (Gachene, 2014), which ordinarily show resistance to water erosion. These volcanic soils have structural/ aggregate stability, high infiltration rate and high porosity (Poulenard *et al*., 2001) which resist the erosive power of rainfall. However the terrain within the catchment is steep (Ruto, 2015), increasing the kinetic force that is acting on the soil particles. Therefore, the expected behaviour of these soils is linked to vulnerability of the landscape to rainfall intensity and variability and due to the changes in land cover types and uses of the hilly area.

Land use/ cover changes increase soil erosion by one or two orders of magnitude (Montgomery, 2007). This accelerated erosion by water, is a selective process that involves preferential removal of light and fine fractions of low densities of $<1.8 \text{Mg/m}^3$ (Bajracharya *et al*., 2000; Lal, 2002). The kinetic energy of the impacting rain drops along with the shearing force of water disperses aggregates and exposes the organic matter to chemical, physical and biological decomposition (Paustian *et al*., 1997). Therefore being concentrated on the surface and of relatively low density, SOM is easily removed by runoff or wind erosion.

This type of erosion occurs in four stages; (i) detachment of particles, (ii) breakdown of aggregates, (iii) transport and redistribution of sediments over the landscape and (iv) deposition in protected/depressional sites or aquatic ecosystems (Lal, 2005b). Consequently, the SOC is influenced at each stage depending on different soil physical characteristics such as soil moisture and temperature. Eroded SOC may move into riverine, estuarine or marine environments (De Gryze *et al*., 2008) where it can be mineralised by aquatic organisms or stored in sediments.

2.9 Soil erosion- sink or source

There has been a lengthy debate as to whether erosion in its accelerated form is a source or a sink of SOC. One of the traditional school of thought is that erosion is a carbon source (Jacinthe *et al*., 2002; Lal, 2004; 2008). This argument is centred on SOC being carried away from eroding sites and due to the transport process; it is exposed to physical, chemical or biological decomposition, consequently causing loss of SOC on a plot scale (Berhe, 2012). Over the recent past however, new research has shown that on a watershed scale, erosion can be a sink in the depositional sites (Smith *et al*., 2001; Berhe *et al*., 2007; Harden *et al*., 2008). This poses a potential carbon sequestration mechanism as opposed to noneroding sites as long as NPP is maintained on the eroding slopes (Harden *et al*., 1999). The SOC found in topsoil is buried under layers of subsoil and deeper horizons. This protects the SOC from decomposition and oxidation of particulate organic matter (POC) and dissolved organic carbon (DOC) to release CO_2.

2.10 Impacts of gulley erosion

There are onsite and offsite effects of erosion on SOC. In farming systems, the sudden removal of a significant portion of the top soil drastically lowers soil fertility (Govers *et al*., 2004) and reduces land available for production with increase labour costs (Rouw *et al*., 2002). Gullies are also responsible for increased surface drainage with accelerated desertification (Valentin and Poesen, 2005). In open grazing systems there is dissection of the land surface, hindering livestock and wildlife movement (Chaplot *et al*., 2005).

Edaphically, gully erosion carry alluvial deposits to the lower end of the catchment with high levels of nutrient loads causing lateral fluxes of macro and micronutrients (Lal, 2004) such as

SOC, N, and P. Moreover, there is limited water infiltration into the soil, hence low amounts of ground water reservoirs. Research has also shown that there is sizeable damage to construction sites and blocking of roads during a heavy rainfall occurrence (Jahantigh and Pessarakli, 2011).

2.11 Thesis Format

This thesis is written in paper format, divided into six parts. The first chapter deals with the introduction component of land use and land cover changes in world and in drylands specifically. Moreover it covers the scope of the study including objectives, hypotheses and justification of the study. Chapter two takes care of literature of studies done in land use change and its effects on soil organic carbon and soil erosion. Chapters three, four and five are presented in paper format within which each chapter is a complete stand-alone paper including abstract, introduction, methodology, results, discussion, conclusion and references. Specifically, chapter three; Effects of Land Use and Land Cover changes on Soil Organic Carbon and Total Nitrogen Stocks in the Olesharo Catchment, Narok County, Kenya. Chapter four, Assessment of Soil Organic Carbon Fractions and Carbon Management Index under different Land Use Types in Olesharo Catchment, Narok County, Kenya. Chapter five, Soil Organic carbon loss and Sediment loss in relation to Gully erosion Olesharo Catchment, Narok County, Kenya. Chapter six gives the summary of the study finding and gives general conclusions, recommendation and further research need on the major findings.

CHAPTER THREE

Effects of Land Use and Land Cover changes on Soil Organic Carbon and Total Nitrogen Stocks in the Olesharo Catchment, Narok County, Kenya

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3.1 Abstract

Land use and land cover change (LULCC) is the most prominent cause of soil organic carbon (SOC) variability in any landscape. Kenyan arid and semi-arid lands (ASALs) have been facing extensive land use/ cover changes in the last three decades prompting a review on the impacts it has on soil quality and consequently on land degradation. This study was carried out in Olesharo Catchment, Narok County, Kenya. The main objective of the study was to study how the different land use types within the catchment affects SOC and total nitrogen stocks in the catchment. Using LandSat imageries, four land use types were identified: shrubland (SH), agricultural land (AG), grasslands (GR) and barelands (BL). Disturbed and undisturbed soil samples were taken from 30 x 30m plots randomly distributed for each of the LUT at 0-15 cm and 15-30 cm depths for the analysis of SOC/ and TN stocks. The study showed that the means of SOC in land use types were significantly different ($P < 0.05$). Shrublands registered the highest mean total of 31.26 Mg C ha^{-1} which was significantly different from the other land use types. The means of SOC in GR (14.98 Mg C ha^{-1}) and BL

(13.64 Mg C ha^{-1}) were significantly different from SH and AG and were the lowest in SOC concentrations. In terms of TN mean values, SH was the highest (5.29 Mg N ha^{-1}) while BL was the lowest (1.89 Mg N ha^{-1}). Similarly, the mean total of SOC and TN stocks in the surface layers (21.38 Mg C ha^{-1} and 3.65 Mg N ha^{-1}), were significantly higher than the sub-surface (18.74 Mg C ha^{-1} and 2.35 Mg N ha^{-1}) layers indicative of the stocks decreased as depth increased. The results suggest that land use types have influence on SOC and TN and their management can contribute to sustainable land management to mitigate negative effects of climate change.

Key words: soil carbon stocks, nitrogen stocks, land use types

3.2 Introduction

Change in land use and land cover (LULCC) is the leading cause of soil degradation and specifically loss of soil organic carbon (SOC) in the world (Jobaggy and Jackson, 2000). According to Kamoni *et al*. (2007), Kenya is expected to lose 140 TG C by 2030 if the current trend of change in land use and climate continues. Sustainable management of soil, and especially soil organic carbon (SOC), is considered beneficial to soil functions that support plant productivity and most recently in the fight against global climate change (Vagen, 2005; Hoyle, 2011). Occupying only 10% of the soil, SOC consists of organic compounds less than 2mm in size (Cookson *et al*., 2005; Lal, 2008) which include plant, animal and microbial residues at all levels of decomposition that are highly enriched in carbon. Soil organic carbon has significant influence on soil physical, chemical and biological characteristics such as nutrient cycling, soil structure and aggregation, water retention, as well as immobilizing pollutants and heavy metals (Grace *et al*., 2006).

Soil organic carbon is influenced by climate variables, topographical positions, lithological, biotic variables (flora and fauna) and human induced factors (Fernandez *et al*., 2013). Land use change is the most prominent cause of SOC decline in soils (Don *et al*., 2011) responsible for 12 - 20% of greenhouse gases emissions (Van der Werf *et al*., 2009). Over the recent years, research has shown that the capacity of soil to sequester carbon is second only to oceans with a capacity of 1500 Pg to 1 m depth (1 Pg = 1g x 10^{15}) and releases only 4 % of it annually (Smith, 2004; IPPC, 2007; Li *et al*., 2015). This potential scenario to offset global warming has led to linking anthropogenic activities like land use and cover changes management in acting as carbon storage capacities (Schimel, 2001).

Soil nitrogen studies have become popular in recent studies, primarily in agricultural landscapes. This is because of the increase usage of synthetic fertilizer used by farmers in the sub-Saharan Africa (Were *et al*., 2015). There has been a livelihood shift from pure or sedentary pastoralism to agro-pastoralism within the drylands of Kenya which has altered nitrogen fluxes in the ecosystem. Defined consequences of increase use of N-based fertilizers to the atmosphere have been observed especially with the rise of nitrous oxide emissions (Nie *et al*., 2013). In native vegetation such as grasslands, the N-cycle is balanced by the controlled denitrification and volatilization of N compounds. However, poor grazing management alters this cycle leading to low soil-plant N uptake resulting to erosion of nitrogen based compounds to waterways causing eutrophication (Galloway *et al*., 2008).

Land use and land cover changes have become prominent in the Kenyan rangelands due to increase of demographical pressures of both human and livestock as well as local and exogenous opportunities and constraints (Mganga *et al*., 2011). Therefore LULCC has led to soil erosion which is a dominant feature in the Olesharo catchment that has deep gullies stretching over 4 km and 25 m wide and 15m deep (Khalif *et al*., 2015). Previous studies using processed LandSat imageries in Olesharo catchment show that the area is characterised by grasslands, shrublands with pockets of agricultural land and bareland. These images show

how the land use/cover types have changed over three decades of 1988, 2000 and 2011 (Konana *et al*., 2017).

Changes in land use/cover types have impact on soil properties. One such property which is the main focus of this study is change in SOC and TN stocks. The prevailing hypothesis is that a change from forest land to cropland or pastures leads to a decline of SOC stocks because of the decline in biomass production; root mass in dominant vegetation and increasing turnover rates (Schimel, 1986). However, this is also dependant on soil moisture, topological position and type of soil. In contrast, other LUC may lead to an increase in SOC, for instance, conversion from agricultural land to pasture or afforested (Guo and Gifford, 2002; Were *et al*., 2015).

Although there have been numerous researches done on carbon stocks, comprehensive data is still scarce especially for ecosystems on a local scale as well as national carbon inventories (Falloon *et al*., 2007). This study focused on assessing soil carbon and total nitrogen stocks under four land cover types in Olesharo catchment; shrublands, grasslands, agricultural lands and barelands. The soil samples collected were analysed for bulk density, and soil texture for comprehensive understanding of tropical SOC dynamics. Total nitrogen was also considered in this study because of the intricate linkages between carbon and nitrogen cycles.

3.3 Materials and Methods

3.3.1 Description of study site

The study was carried out in Suswa Location, Narok County located in the Southwest of Kenya. The County lies between longitudes 34°45'E and 36°00'E and latitudes 0°45'S and 2°00'S. The topography ranges from a plateau with altitudes ranging from 1,000 - 2,350 m a.s.l. at the southern parts to mountainous landscape (3,098 m. a.s.l) at the apex of Mau escarpment in the North (Serneels and Lambin, 2001; Jaetzold *et al.*, 2010; Ruto, 2015).

The Catchment is found within agro-climatical zones (ACZ) IV which is semi-humid to semi-arid (NEMA, 2009). The area experiences bi-modal pattern of rainfall with long rains expected from mid-March to June and short rains from September to November. The local fluctuations in topography influence the rainfall distribution patterns, with the highlands receiving as high as up to 2000 mm/yr. while the lower and drier areas receiving less than 500 mm/yr. (Ojwang *et al.*, 2010).

Suswa area has steep gradient and volcanic-ash soils, mainly Andosols, which are prone to erosion. There are visible patches of bareland that have developed due to overgrazing. The Suswa hill is dominated by an intricate network of deep gullies reaching to 4km in length, 25 m deep and widths of over 30 m (Khalif *et al*. 2015). There are also pronounced cattle tracks evidence of intense runoff and flash floods during the rains (Odini *et al*., 2015). The area is dominated by scattered acacia tree species and *Thaconathusz camphoratus* which is an indication of dry weather conditions and depressed rainfall amounts (Reed *et al*., 2009).

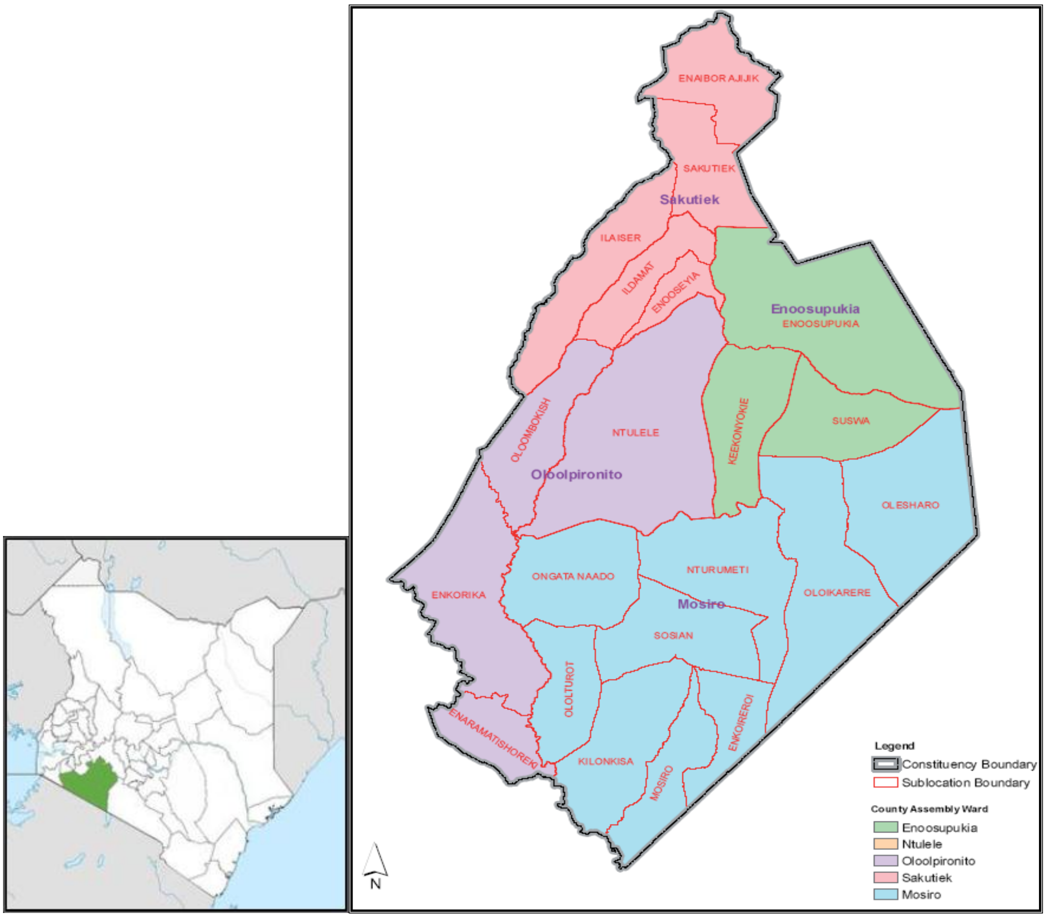

Figure 3.1 The study area in Narok County

3.3.2 Land use

Narok County has diverse land use types spanning the agroecological zones that occur in the area. The catchment is found within the Narok County which is predominantly a semi-arid climate. Olesharo is found within the lower elevations of the County where there is a prominent transition from pastoralism to agro-pastoralism. The area is dominated by shrubland and grassland with patches of agricultural land and bareland (Table 1). Croplands have grown in the recent decade as a way to diversify production due to the changing climate. Farming is a monocrop of maize (Kenyan staple crop), and or an intercrop of maize and beans. Sheep, goats and beef/ dairy cattle is the predominant livelihood activity, with bee keeping in selected households (Jaetzold *et al*., 2010; Maina *et al*., 2013). The area is also populated with wildlife which is exploited for tourism and ecotourism (Skidmore and

Ferwerda, 2008). The community land has now been partitioned therefore wildlife and livestock mobility is curtailed; this in turn has had severe detrimental effects on soil erosion.

Table 3.1. Land use/ land cover change in Mount Suswa Catchment (1985-2011)

Land use/cover	1985 Area (Km^2)	%	2000 Area (Km^2)	%	2011 Area (Km^2)	%	%change 1985-2000	%change 2000-2011	%change 1985-2011
Built up Area	0.77	0.19	0.91	0.24	1.30	0.32	+18.18	+42.86	+68.83
Agricultural Land	1.00	0.02	15.33	3.81	23.16	5.76	+1433	+51.08	+2216
Shrubland	231.1	57.4	170.6	42.4	237.8	59.1	26.18	+39.39	+2.90
Bareland	1.21	0.30	12.44	3.11	2.46	0.61	+928.1	+405.69	+103.3
Grassland	166.71	41.45	188.92	46.97	137.68	34.2	+13.32	-27.12	-17.41

Source: Konana et al., 2017

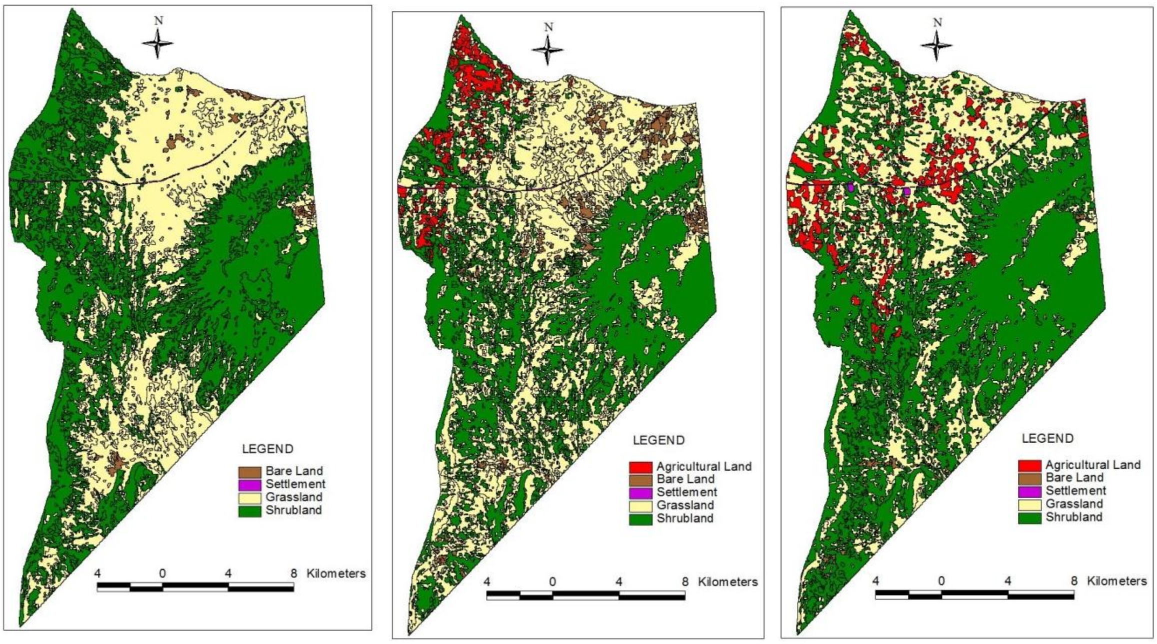

Figure 3.2. LandSat imageries of land use/ cover types map in year 1985, 2000 and 2011 from table 3.1 of Olesharo Catchment: Source: Konana et al., 2017

3.3.3 Suswa soils

Suswa area has humic Andosols, well drained, relatively deep, dark brown, friable and smeary, sandy clay to clay, with acidic humic topsoil (Sombroek *et al*., 1982; Jaetzold *et al*., 2010). These soils have sand to silt clay ratio of 2:1 on average for the horizons studied (Gachene, 2014). The high silt /clay ratio, low organic matter and high bulk density which may be due to compaction as a result of continuous grazing in the area, among other factors, have made the soils to be more vulnerable to soil erosion. The soils are stratified with hard pans underlain by soft clayish strata that are readily eroded (Maina, 2013).

3.3.4 Sampling Design and Soil Sampling

Sites were selected to minimize soil variability. Six plots per each LUT of 30 x 30 m were randomly selected and laid on the different land use types that were identified using the Landsat maps (Fig 3.2): agriculture, bare land, grassland and shrubland. In each plot, disturbed soil samples were collected from each corner and one at the centre at two depths, 0-15 cm and 15-30 cm, using an auger. Consequently, all the samples collected at each depth per plot were combined to make a composite of 500g. For dry bulk density, cylindrical core rings (5 cm dimensions) were used to collect undisturbed samples per depth from the centre each plot. Geographical position and elevation of each plot were also recorded. Forty eight soil samples per land use were collected making a total of 192 samples.

3.3.5 Physical and Chemical Soil Analysis

The collected soil samples were air-dried, ground and sieved through a 2 mm sieve to remove any visible plant residues. Concentration of SOC was estimated through the Walkley-Black wet oxidation method (Nelson and Sommers 1982), TN concentration through Kjeldahl digestion method (Bremner and Mulvaney, 1982). For bulk density, the samples in the core rings were oven dried at 105˚C for the standard 48 hours. (Blake, 1965), and determined by dividing the weight of the dry soil by volume of the core rings. Soil texture was determined through the hydrometer method after dispersing soil with sodium hexa-metaphosphate solution to eliminate organic matter (Day, 1956).

3.3.6 Estimation of Soil Organic Carbon stocks

The SOC and TN stocks were calculated using the equation

$$SOCst = \frac{SOC}{100} \times BD \times D \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq1}$$

Where: SOCst is the soil organic carbon stock (Mg C ha^{-1}); SOC is the soil organic carbon concentration (%), which is then converted to g C g $^{-1}$ soil; BD is the bulk density (g cm^{-3}); D is the depth (cm); which we multiply by 100 to change from g C / cm^{2} to Mg C /ha^{-1}. For TN stock the SOC was substituted with TNst Mg N / ha $^{-1}$ (Were *et al*., 2015).

3.3.7 Statistical analysis

Analysis of variance (ANOVA) and Duncan's multiple range test (DMRT) for comparison of means were performed using software SAS 9.1.3.The statistical significance was determined at $P < 0.05$.

3.4 Results and Discussion

3.4.1 Effect of land use and land cover types on SOC and TN concentrations.

The highest SOC (2.23%) and TN (0.35%) percentages were recorded under shrublands while the C/N rations were not significantly different (Table 3.2).

Table 3.2 Means of SOC%, TN% concentrations and C/N ratios in different LUTs

LUTs	0-15cm			15-30cm		
	%SOC	%TN	C/N	%SOC	%TN	C/N
GR	0.886^a	0.1672^a	5.29^a	0.787^a	0.1269^{ab}	6.24^a
SH	2.226^c	0.3492^b	6.38^a	1.89^c	0.2074^c	9.11^a
AG	1.413^b	0.2818^b	5.01^a	1.408^b	0.1886^{bc}	7.46^a
BL	0.756^a	0.1129^a	6.70^a	0.669^a	0.0759^a	8.81^a
$LSD_{0.05}$	0.25	0.12	3.75	0.32	0.07	7.17

GR-grasslands; SH- Shrublands; AG- Agricultural lands; BL- Barelands; SOC- soil organic Carbon; TN- Total Nitrogen; C/N- Carbon Nitrogen ratio. Note: Means down the same column with different letters indicate highly significant ($P < 0.05$).

Percentage SOC and TN were low in all the four land use types. Results show that there was a significant difference between % SOC in SH and AG as compared to the GR and BL. Grasslands and bare-lands were not significantly different from each other ($P< 0.05$). Soils in the shrublands registered high % SOC followed by agricultural land while GR (0.89%)and BL had the least (0.76%). For TN, the shrubland had the highest amount (0.35%) though not significantly different from agricultural lands. However, the two LUTs were significantly different from BL and GL. The barelands had the lowest total nitrogen of (0.08%) which was not significantly different from the grasslands. In all the land use types, the SOC and TN concentrations were higher on the surface (0-15 cm) than in the sub-surface (15-30 cm).

The average SOC of 1.6 % is below that observed by Batjes (2004) working in on a SOC inventory in Kenya which ranged from 4.6 - 4.7 % for ACZ IV. The lowest SOC % was observed in the barelands, which can be attributed to low above-ground litter production that provides substrates for mineralization. This may be attributed to the fact that Batjes results were an average of samples from different areas in the AEZ while this research was highly site specific. Moreover the level of degradation at the time of sampling was higher than in 2004. Similarly studies done by Kurgat (2011) in northern Kenya showed that BL exhibited low SOC due to low moisture availability as well as poor soil structure that would increase microbial population. Other studies also show high SOC concentrations can be attributed to shrub canopies which are consistent with their high litter cover and soil moisture content (Stavi *et al* ., 2008). Higher SOC in shrubland compared to AG, is accredited to effective root systems of shrubs and acacia (*Olea africana, Albizia gumifera, Cordia ovalis, Croton dichogamus, Carrisa edulis* and *Tarchonanthus camphoratus*) (Reed *et al*., 2009; Maina *et al*., 2013). In the ASALs of Kenya, Dabasso *et al*. (2014) showed that soils in SH had 38 % of C as opposed to 32% that of GR. Comparable results by Fu *et al*. (2010), elucidate that SOC concentrations are lower in croplands that had been converted from native vegetation due to increase in soil temperature and evaporation rates from crop harvesting.

The SOC in AG was higher than grassland (Table 3.2) and this could be attributed to the stubble (maize stocks) left on the farm as also observed during the time of sampling. The farmers also practiced intercropping of maize and beans with fertilizer and animal manure application. This provides litter at different stages of decomposition. Solomon *et al*. (2000) found that farming techniques that leave material on the farm after harvesting controls carbon fluxes thereby increasing carbon inputs. The litter controls soil moisture and temperature attracting large populations of microorganisms hence improve soil properties (Lal, 2004).

Grasslands unexpectedly had 16 % SOC and TN (18 %) lower than SH. This may be attributed to overgrazing, decreasing soil fertility and biodiversity within the catchment. Verdoodt *et al*. (2010) working in the Njemp flats of Kenya showed that low SOC in open community grazing lands are as a result of low herbaceous biomass production due to poor grazing management. Comparable results were reported by Batjes (2004) in soil inventory done for Kenya that reported that GR had low SOC due to lower net primary productivity (NPP) as compared to SH within the same ACZ. These results are contrary to other studies which indicate that grasslands contain higher SOC than croplands and shrublands in North America (Franzluebbers *et al*., 2010). They attribute the increase to the high rates of turnover of less recalcitrant material than shrubland and sustainable grazing management practice.

3.4.2 Soil organic carbon and Nitrogen stocks

Figure 3.3 shows the mean total SOC stocks in Mg/ ha (1Mg = 1000kg) in different land use types. The BL surface soil had the lowest SOCst of 13.64 Mg C ha^{-1} whereas the SH had the highest at 33.78 Mg C ha^{-1}. Both SH and AG were significantly different in the surface layer at $p < 0.05$. Grasslands had lower SOCst (14.88 Mg C ha^{-1}) compared to AG (23.13 Mg C ha^{-1}). For the sub-surface layer, SH still had the highest SOCst at 28.77 Mg C ha^{-1} while BL the lowest (12.05 Mg C ha^{-1}). Both SH and AG were significantly different from the other land use types at $p < 0.05$, while GR and BL were not significantly different from each other. In all the land uses, the upper surface layer had higher SOCst from the sub-surface layer.

Figure 3.4 shows the mean total TN stocks in the different land use types. The BL surface soil registers the lowest TNst of 1.89 Mg N ha^{-1} (1.1 t ha^{-1}) while the SH has the highest 5.29 Mg N ha^{-1}. GR has low stocks of 2.77 Mg N ha^{-1} while AG has 4.66 Mg N ha^{-1}. For the sub surface layer, SH have stocks of 3.15 Mg N ha^{-1}followed by 2.95 Mg N ha^{-1} in AG. Grasslands exhibits 1.99 Mg N ha^{-1} and the least is BL having recorded 1.32 Mg N ha^{-1}. At both depths, there was no significant difference in TNst between BL and GR, however there was a significant difference between SH, AG and the BL/GR

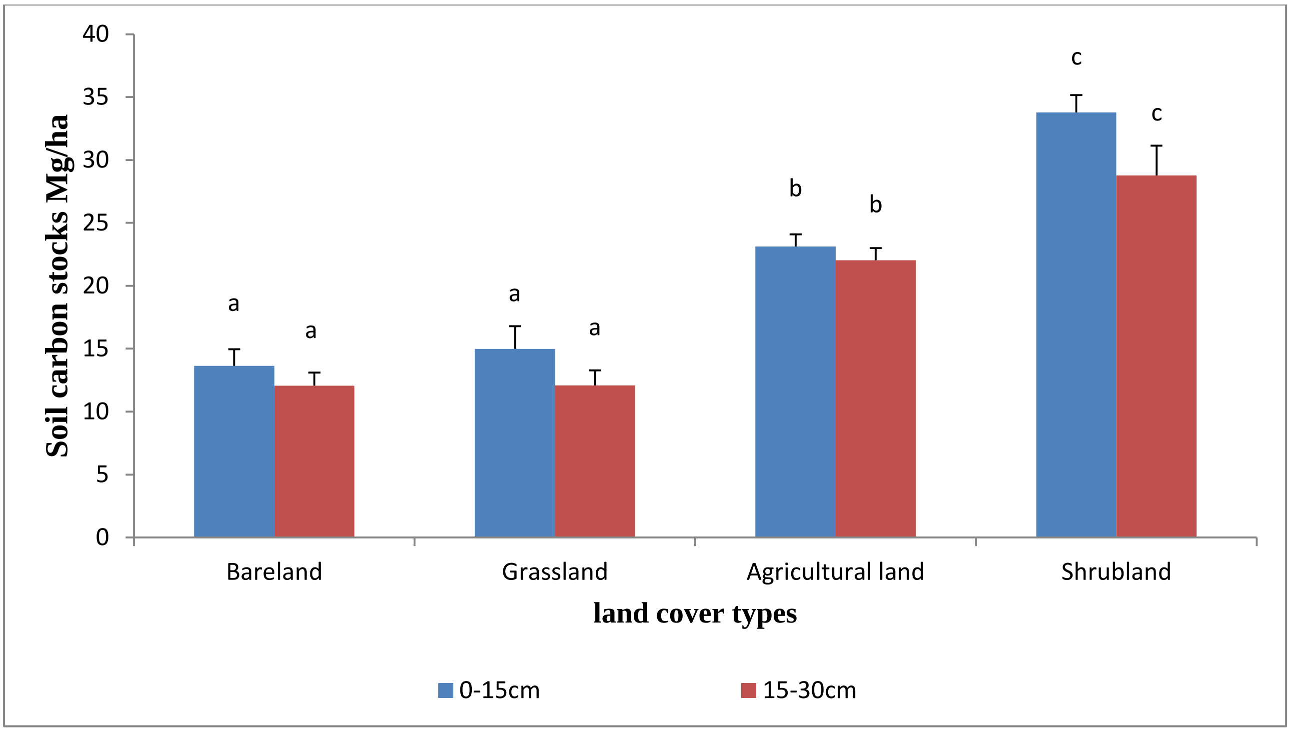

Figure 3.3 Total carbon stocks under different land cover types. Note: Means in the same colour with different letters indicate highly significant (*P* < *0.05*)

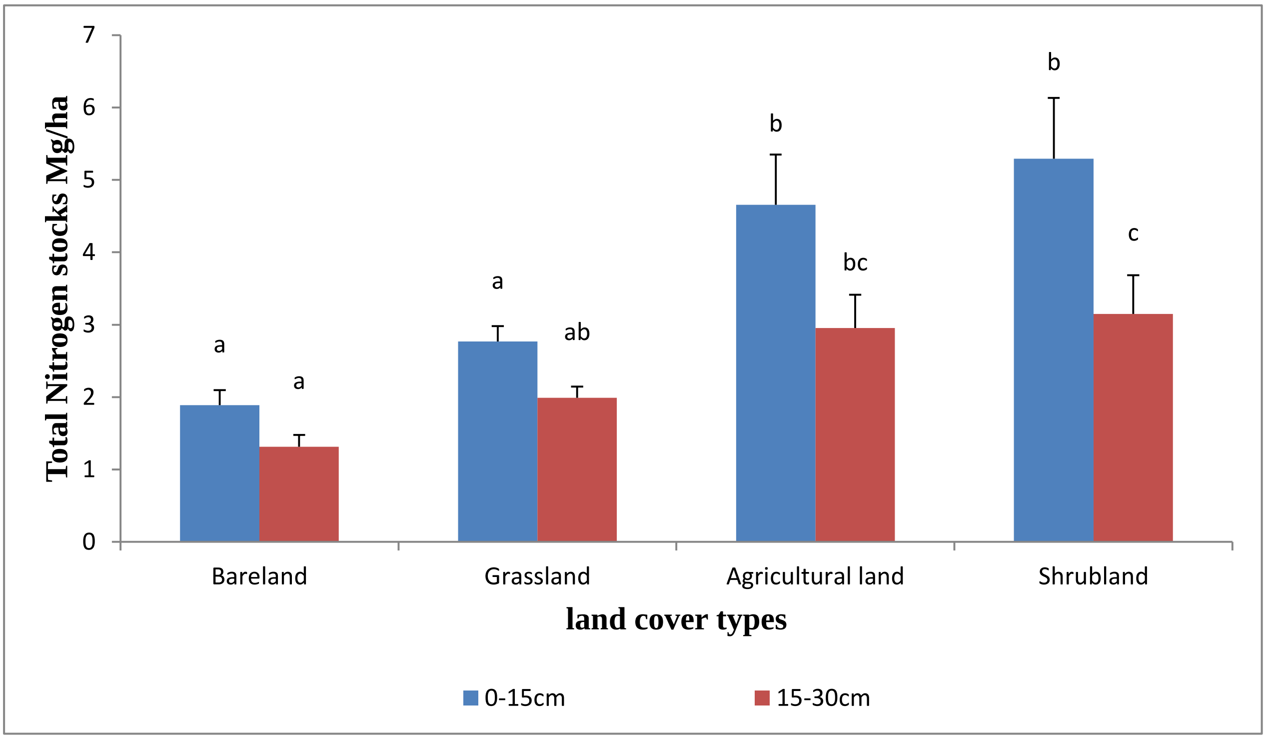

Figure 3.4 Total nitrogen stocks under different land cover types. Means in the same colour with different letters indicate highly significant (*P*< *0.05*)

Higher soil organic carbon and total nitrogen stocks were recorded in the SH compared to all the other land cover types. This may be attributed to higher litter input and soil moisture found under the canopies within the shrubs. Consequently, the microclimate (increased moisture, reduced soil temperature) created encourages microbial action on the litter leading to high organic carbon content in the soil which improves soil aggregate stability (Reeder *et al*., 2004). The average SOCst in the SH are similar to those obtained under the GEFSOC study by Kamoni *et al*. (2007), which ranged from 0 - 18 t ha^{-1}. The area under shrubland has been fenced by local communities in order to control grazing within the catchment. Studies that elucidate effects of enclosures on SOCst have shown there is a significant increase of SOC and TN stock due to controlled harvest of biomass (Han *et al* 2008; Sanjari, 2008; Wasonga, 2009; Mureithi *et al*., 2014). Since the SH occurs in the high altitudes areas of the catchment, there have been several measures to control erosion using physical measures like cut-off dams, semi-circular bunds , gunny bag check dams, water retention ditches and retention dams. These structures have encouraged infiltration and enhanced soil moisture content leading to soil organic carbon build up.

A study done by Dabasso (2014) in northern Kenya and Mganga *et al*. (2011) in Kibwezi showed similar results between SH and GR. They attributed the results to higher herbaceous cover which facilitated higher residue turnover compared to the grasslands. However, divergent results have also been registered. For example, Derner *et al*. (2006) working in the North American plains reported that areas under continuous heavy grazing had more organic carbon than areas that were lightly stocked. They linked this result to higher root biomass that was found under high grazing areas. In the current study, the results show that the land cover type and controlled grazing do affect the SOCst.

Unexpectedly, GR had lower SOCst compared to SH and AG. This may be linked to the uncontrolled grazing within the catchment. The subsequent disruption of carbon inputs and excessive harvesting of above ground biomass by livestock alters the C cycle within the ecosystem. This excessive removal of herbaceous material has also led to exposure of the surface to harsh temperature and surface runoff, which further aggravates the situation. According to Murty (2002), this exposure hastens the litter turnover rates, leading to SOM oxidation, expediting CO_2 release into the atmosphere.

In the grasslands of northern Kenya, Muya (2011) reported that low SOCst has been as a result of soil compaction, pulverization, particle soil dispersion, low organic inputs, high pH and high exchangeable sodium percentage. Further, the catchment has low and variable precipitation, with high solar radiation (Jaetzold, 2010) which discourages SOC build up. Agricultural land showed relatively high SOC over GR but lower than SH and can be attributed to the stubble remains on the farms and animal manure use. This is consistent with studies that aim to use sustainable agricultural practices to reduce CO_2 by reduced or no tillage; use of crop residues; intercropping and mixed cropping (Chivenge *et al*., 2007; Batlle-Aguilar, 2010). A recent study in Brazil saw the increase of SOC in integrated crop-livestock management systems where crops, especially soybeans and grasses were planted together to reduce rangeland degradation and provide incentives for dryland conservation (Batlle-Bayer, 2010).

The total nitrogen stocks are highest in SH and lowest in BL. Grasslands unexpectedly show low TNst than AG or SH. This is in contrast with the findings of Frank *et al*. (2004) working in Yellowstone National park that show grazing increases TNst through animal faecal matter and urine that are deposited on the surface. The current study area is under intense gully erosion that has resulted in general degradation of the area. Work done in the Tibet highlands show grasslands that experience erosion register general low TNst (Nie *et al*., 2013). Besides, high TNst would be registered if the amount of input by animals exceeds that which is taken away. Moreover, due to high temperatures and low precipitation, nitrogen volatilization from

NH_3 which is the loss of nitrogen as free ammonia (NH_3) could have contributed more to loss of N (Alphayo, 2015).

The SOCst and TNst in all land use types decreased with an increase in depth. This is attributable to reduction of litter fall rich in organic matter inclusive of root exudates and leachates which are often found on surface horizons. There is minimal rainfall in the area with steep slopes and therefore leaching is not a factor. The lower concentrations and stocks of SOC in the subsurface soils thus correlate to the corresponding BD values observed within the different LUTs (Demessie *et al*. 2013; Li *et al*. 2013; Zhang *et al*. 2012, 2013; Wang *et al*. 2010; Yimer *et al*., 2007).

3.4.3 Amount of SOC and TN in the land use types in Olesharo Catchment

Shrublands registered the highest amount of soil organic carbon with 1,487,501.55 tons in 237.81 km^2 while BL had the lowest with 789.66 tons in 2.46 km^2.

Table 3.3 Total amount of SOC and TN stock in different land use types based on acreage

Land use/cover	LU acreage Km^2	Total SOCst 0-30cm ($Mg\ C\ ha^{-1}$)	Total TNst 0-30cm ($Mg\ C\ ha^{-1}$)	Total amount of SOC/LU (Tons C)	Total amount of TN/LU (Tons N)
GR	137.68	27.07	4.76	372,699.76c	65,535.68c
SH	237.81	62.55	8.44	1,487,501.55d	200,711.64d
AG	23.16	45.17	7.61	14,273.72b	17,624.76b
BL	2.46	25.69	3.21	6,319.74a	789.66a

GR-grasslands; SH- Shrublands; AG- Agricultural lands; BL- Barelands; SOCst- soil organic Carbon stock; TNst- Total Nitrogen stock

All the LUTs are significantly different from each other, with AG having 14,273.72 tons C in 23.16 Km^2 and GR with 372,699.76 tons C in 137.68 km^2. For total nitrogen, the highest is in SH with 200,711.64 tons N and the lowest is BL with 789.66 tons N. All the land uses were significantly different from each other.

Shrublands have the highest total SOC and TN amounts based on its acreage and stocks. This is attributable to the large acreage and little area change that has occurred on it for the last three decades (Konana *et al*., 2017). Moreover this may be attributed to minimal grazing on the SH which are found in steep topography and preference to the grasslands found in gentler slopes. This is in contrast to results found by Muya *et al*. (2011) who observed less SOC stocks in the higher slope position as opposed to lower. This however was due to low soil cover on the upper slope positions due to disturbance. In the SH of Olesharo, there is minimal disturbance therefore increasing litter on the surface. Grasslands on the other hand, have lower SOC and TN stocks per the acreage. This may be due to the overall overgrazing and exposure to erosion mechanisms.

3.5 Conclusions and Recommendations

The study shows that land use/ land cover type has influence on SOC and TN distribution in the catchment. Despite being in the same catchment, different land use types had significantly different SOCst where SH exhibited high levels of SOC which could be attributed to higher litter deposition, soil moisture content, C:N ratio and grazing management. From the total acreage, the differences in total SOC and TN from each LUTs are evident. The study has also elucidated that overgrazing has severe impacts on SOC and TNst loss which provides for an indicator for soil quality and soil degradation within the catchment. The study reinforces the results of other studies in the same area that link land use change with the development of the deep gully network within the catchment. Furthermore, the results give a deeper understanding on the potential use of land use and its management to sequester carbon in line with global strategies to address the negative effects of climate change.

From this study, it is recommended that proper holistic grazing strategies should be employed by the pastoral communities to counter the deleterious effect of overgrazing within the catchment. Due to the dynamism of land use change coupled with the steep topography, effective soil conservation strategies should be put in place especially in the agricultural lands, which based on the current practices, seems to be a good sink for SOC. The study also recommends the use of SOC modelling to predict future trends of SOC losses under the different land use types and different climatic scenarios in order to influence policy.

Acknowledgements

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CHAPTER FOUR

Assessment of Soil Organic Carbon Fractions and Carbon Management Index under different Land Use Types in Olesharo Catchment, Narok County, Kenya.

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4.1 Abstract

This study, carried out in Olesharo Catchment, Kenya, investigated the effect of different land use types on soil organic carbon fractions and assessed soil quality using the carbon management index (CMI). Soil samples were collected from four land use types in the Olesharo Catchment, mainly, grassland, shrubland, agricultural land and bareland. Soil sampling points were identified by Landsat imageries and the soil samples taken at 0-15 cm and 15-30 cm from six 30 x 30 m plots per land use type. The soils were analysed for total organic carbon (TOC), particulate organic carbon (POC) and mineral organic carbon (MOC). Further, the CMI for each land use type was calculated using shrublands as the reference land use. The study showed that the means of TOC, POC and MOC were significantly different between each land use at $p < 0.05$. Shrublands had significantly higher TOC (22.26 g kg^{-1}) than grasslands (10.29 g kg^{-1}) and barelands (7.56 g kg^{-1}), but were not significantly different from croplands (14.13 g kg^{-1}). Particulate organic matter (POC) was more sensitive than mineral organic carbon (MOC) in all the land use types and shrublands had significantly higher POC (7.79 g kg^{-1}) than all the other LUTs ($p < 0.05$). Grassland (2.46 g kg^{-1}) was significantly different from bareland (1.51 g kg^{-1}) and cropland (3.82 g kg^{-1}). The MOC was significantly higher in SH (10.04 g kg^{-1}) while BL was lowest with (4.24 g kg^{-1}). The MOC was higher than the POC across the depths in all the land use types. The CMI was highest in AG and lowest in BL referenced to SH. The study revealed that the POC fraction was more sensitive to different LUTs especially in grasslands, due to overgrazing which had detrimental impacts to soil organic carbon. Therefore proper management to maintain the POC fraction will enhance soil quality within the catchment.

Key words: Land use types, particulate organic carbon, mineral organic carbon, carbon management index, Olesharo catchment.

4.2 Introduction

Increasing anthropogenic disturbances especially on land use/ cover change (LULCC) is the major cause of soil quality deterioration in the world (Haynes, 2005). Soil organic carbon (SOC) has recently gained prominence in the assessment of soil quality since it has a compounding effect on the chemical, physical and biological aspects of the soil. Though described by some as the least most understood component of the soil because of its dynamism, (Lehmann and Kleber, 2015) SOC has been linked to its potential role in carbon sequestration through proper management of land use and cover types (Yang *et al*., 2012). Land use and land cover types influence C fluxes in an ecosystem through litter quality, deposition and turnover rate. Although SOC is an indicator of soil quality, conceptualization of soil fractions can be used to detect slight changes in management and regulate degradation (Blair *et al*., 1995; Diekow *et al*., 2005).

Soil organic matter can be partitioned, into several fractions depending on their densities. Labile fraction (LF) has a high turnover rate due to its high sensitivity to management systems and soil erosion (Six *et al*., 2002; Berhe *et al* 2012; Wang *et al*., 2014; Kapkiyai *et* *al*., 1999; Murage *et al*., 1998). Labile fraction comprises of particulate organic carbon (POC) (53~2000µm), light fraction organic carbon (LFOC) (density of <2.0g cm^{-2}) which can be separated into free and occluded POC, readily oxidized carbon (ROC) (easily oxidized by potassium permanganate), soil microbial biomass carbon (SMBC) and dissolved organic carbon (DOC) (Weil *et al*., 2003; Mirsky *et al*., 2008; Cao *et al*., 2013).

The labile fraction (LF) consists of the mineral-free SOM composed of partly decomposed plant and animal residues with a rapid turnover rate and have a specific density that is comparatively lower than that of soil minerals (Alvarez and Alvarez, 2000). Agricultural soils have been seen to have the lowest LF (Murage *et al*., 2001; Vieira *et al*., 2007) due to high disturbances by tillage practices and harvesting of crop residues. In native land cover types (forests, grasslands, shrublands) however, high LF have been registered due to high litter input and controlled soil temperature with little soil disturbance. In grasslands, increase of carbon lability has been linked to activation of microbial activity by enzymes found in the saliva and dung by ruminants especially in tropical areas. (Hamilton and Frank, 2001; Melillo *et al*., 2002; Knorr *et al*., 2005; Rui *et al*., 2011). Moreover the removal of biomass promotes plant regrowth, expediting nutrient cycling within the rhizosphere. The Labile fraction of SOM however reduces with increase in grazing intensity, an observation attributable to low litter deposition, high mineralization due to exposure to surface temperature and intensive erosion (Cao *et al*., 2013)

Stable fraction (SF) accounts for 90% of the total organic carbon (TOC) in terms of particle size distribution (Six *et al*., 2002). This fraction of organic matter is recalcitrant and thus not easily affected by land use or management practices (Bayer *et al*., 2002). Other studies have shown that the stable SOM fraction is more affected by land management practices that the labile portion (Klotzbucher *et al*., 2011; Nyawade *et al*., 2015). This is mostly in agricultural systems in tropical regions where intensive tillage practices disrupt soil aggregates consequently deterring SOM accumulation (Feller and Beare, 1997). Recalcitrance of stable SOM fraction is ascribed to its association with clay particles which fix the carbon protecting it from enzymatic action (Allen *et al*., 2010).

There are different techniques that partition the fractions into functional pool. In this study the physical fractionation based on particle size of organic matter was used as opposed to the conventional $KMnO_4$. Researches against the latter address the limitations that the concentrations are often too strong and therefore detection of changes in the lability often goes unnoticed (Blair *et al*., 1995; Shang and Tiessen, 1997). Moreover, other studies show that the reaction times are not standard as they differ with the soil sample moisture and the decomposition of $KMnO_4$ when exposed to light (Weil *et al*., 2003). Support of physical fractionation is based on the fact that the process is able to disintegrate the POC particles to effectively detect the LF as opposed to the chemical method which is a surface attack and may provide underestimate values of the fractions (Baldock and Nelson, 2000). Therefore the use of sieves to separate SOC fractions was employed following the study by Camberdella and Elliot (1992), where labile fractions are to be found between sieves of sizes 53-250µ and the stable ones < 53µ.

Although total soil carbon varies with soil management, it is not as sensitive as the labile fraction in short durations (Leifeld and Kogel- Knabner, 2005). Therefore, calculation of the lability of SOC within each land cover type can be used as an early indicator for soil degradation or improvement in response to different management practices (Kapkiyai *et al*., 1999). In order to use more sensitive indicators, the development of carbon management index (CMI) has been used in different land uses to evaluate the capacity of a land use to promote soil quality (Blair *et al*., 1995; 2006). It involves the calculation of lability which is the ratio of the labile carbon to the non-labile carbon. This is an assessment model that shows how land use affects the soil quality relative to a reference land use and provides better options for C rehabilitation (Benbi *et al*., 2015). Studies that use CMI as an assessment tool are rare, and therefore the objective of this study was to investigate the SOC dynamics in each LULUCs types of the Olesharo Catchment area, Narok, Kenya and develop a carbon management index.

4.3 Materials and methods

4.3.1 Description of study site

Refer to chapter three materials and methods

4.3.2 Land use

Refer to chapter three materials and methods

4.3.3 Suswa soils

Refer to chapter three materials and methods

4.3.4 Sampling design and soil sampling

Six plots of 30 x 30 m were randomly selected in each land use type as identified using the landsat maps (Figure 3.2) cropland, bareland, grassland and shrubland. Soil samples were collected from every plot using soil auger at two depths (0–15 cm and 15-30 cm), each comprising of a composite of five randomly distributed replicates along a zigzag line. Geographical position and slope of each plot were measured using hand held GPS device and clinometer, respectively. A total of 48 soil samples were collected from n sampling points, covering each of the land use types.

4.3.5 Soil physical and chemical analysis

The SOM was fractionated following procedures described by Camberdella and Elliott, (1992). Air-dried sub samples were sieved and 20 g placed in 250 ml plastic bottle. Sodium hexa-metaphosphate solution (70ml) was added and the mixture shaken for 15 hours on an end to end shaker. The content was passed through a series of sieves (2mm, 250 µ and 53 µ) and the fractions collected dried at 50°C for 48 hours in an air oven. The 53µ-2000 µ fraction was referred to as labile SOM. All the material that passed through the 53µ sieve was collected in a flask, swirled to mix thoroughly and a sample of 100 ml taken and oven dried. This sample was referred to as the stable SOM. The oven-dried fractions were ground using mortar and pestle to a fine material, sieved through 0.149 mm and analysed for SOC (Nelson and Sommers, 1996).

4.3.6 Carbon management index

The carbon management index was computed using equation 1.0.

$$CMI = CPI * LI * 100 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{ Eq (1)}$$

Where CPI is the carbon pool index and LI is the lability index of the soil under a particular landuse (Blair *et al*., 1995).

$$\text{CPI} = \frac{\text{Total carbon in the treatment (g kg}^{-1}\text{)}}{\text{Total carbon in the reference}(g\ kg^{-1})} \ldots\ldots\ldots \text{Eq (2)}$$

$$LI = \frac{\text{L in the treatment}}{\text{L in the reference}} \qquad \ldots\ldots\ldots \text{Eq (3)}$$

Where L is carbon lability of the soil

$$\text{L} = \frac{\text{Content of labile C}}{\text{Content on non−labile C}} \qquad \ldots\ldots \text{Eq (4)}$$

In this study, the native shrubland was used as reference land use. This is because shrubland has been under rehabilitation for the last 4 years and it is enclosed from grazing and other disturbances.

4.3.7 Statistical analyses

The data was subjected to analysis of variance using SAS 9.1.3. Means were separated using the Duncan's multiple range test, with differences considered significant at $P \leq 0.05$. Multiple linear regression analysis was applied on the dataset to identify the factors explaining variability in the observed result.

4.4 Results and Discussion

4.4.1 Effect of land use types on soil organic fractions

Shrublands recorded the highest TOC with 22.26 g kg^{-1} at the surface layer and 7.56 g kg^{-1} in the sub-surface layers.

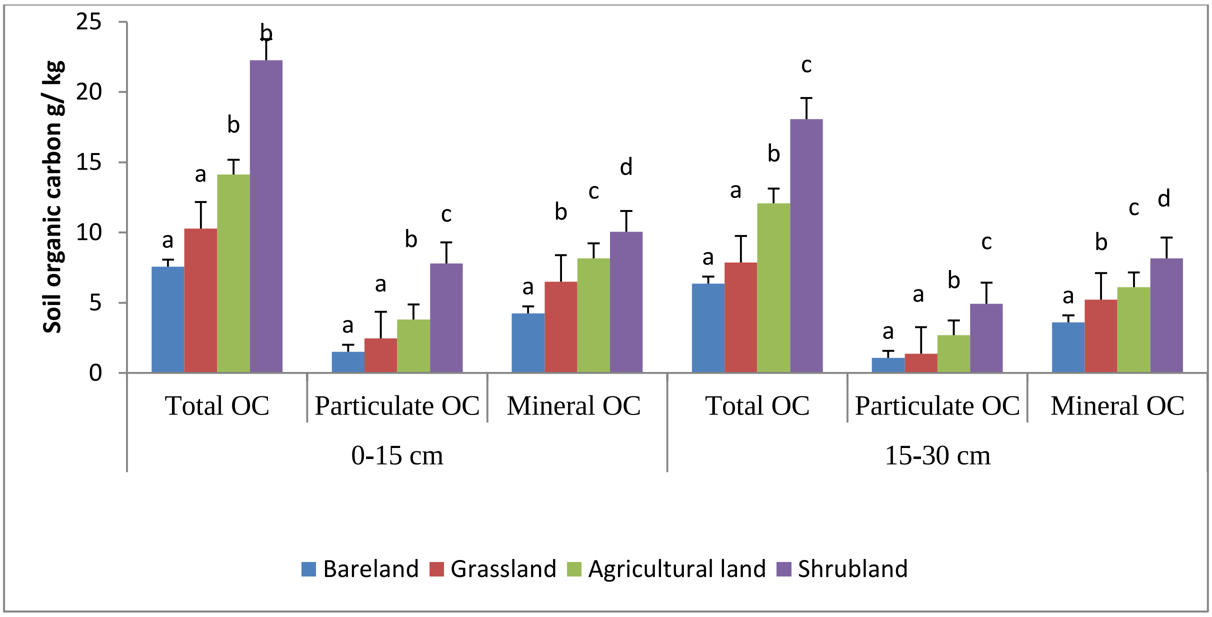

Figure 4.1 land use type effects on soil organic matter fractions at different depths. Note: Bars followed by same letter for each of the depth are not significantly different at $p \leq 0.05$.

Total organic carbon was significantly different between all the LUTs at 0-15 cm (Figure 4.1). In the sub-surface, BL and GR were not significantly different, and both were low compared to SH and AG. Shrubland recorded the highest TOC (18.06 g kg^{-1}) which was significantly different from AG (12.07 g kg^{-1}). TOC was higher in the 0-15 cm than in 15-30 cm.

For POC, shrubland had the highest (7.79 g kg^{-1}) which was significantly different from the other LUTs (Figure 4.1). Agricultural land had (3.82 g kg^{-1}) while GR had (2.46 g kg^{-1}) which was not significantly different from BL (1.51 g kg^{-1}) at the surface layer. At 15-30cm SH and AG were significantly different at 4.93 and 2.70 g kg^{-1} respectively. In GR and BL, the POC was lower compared to the other LUTs but were not significantly different from each other at 1.37g $kg^{-1}$and 1.08 g kg^{-1} respectively.

Mineral organic carbon at 0-15 cm was higher than in 15-30 cm across all the LUTs. All the LUTs were significantly different in mean MOC, with SH (10.04 g kg^{-1}) being the highest. AG (8.17 g kg^{-1}), GR (6.49 g kg^{-1}) and BL (4.24 g kg^{-1}) recorded the lowest. At 15-30cm, SH was the highest (8.15 g kg^{-1}) and was significantly different from the other LUTs. AG and GR were not significantly different from each other recording (6.10 g kg^{-1}) and (5.23 g kg^{-1}) respectively. BL was the lowest at (3.60 g kg^{-1}).

Shrublands had significantly high TOC (Figure 4.1) which may be attributed to above and below ground biomass found in SH consistent with the species found in the area coupled with the enclosure system endorsed by the community which restricts grazing within the LUT. The organic matter accumulation is aided by soil moisture retention and regulated soil temperature provided by the canopy of shrub species (*Albizia gumifera, Cordia ovalis, Croton dichogamus, Carrisa edulis* and *Tarchonanthus camphoratus*). These results are corroborated by Mganga *et al*. (2015) in the southern ASALs of Kenya, illustrating that SH increases TOC due to high carbon inputs from *Acacia senegal* species that increases plant litter in the upper soil horizons, although other studies show that tree root material has a greater influence on soil organic matter in the surface horizon than litter in the short term (Rumpel and Kogel-Knabner, 2011). Other work on erosion studies have shown that surface cover reduces impact of wind and water erosion on surface horizons (Berhe *et al*., 2012, Lal, 2004; Jacinthe *et al*., 2002; Devagiri *et al*., 2013; Yu *et al*., 2013).

Total organic carbon was lower in AG compared to SH. This may be due to the tillage practices that destroy soil aggregation and exposes organic matter to factors such as high soil temperature that encourage faster decomposition rate and erosion. Gelaw *et al*. (2015) working in Ethiopia showed that minimal disturbances on soil surfaces encourage microbial activity which increases TOC in the soil. Moreover, the harvesting of above ground biomass for animal feed instead of leaving it as stubble contributes to lower TOC (Six *et al*., 1998; Wang *et al*., 2009).

In the GR, the TOC was lower which may be attributed to the high grazing intensity within the catchment. Overgrazing affects carbon fluxes whereby the carbon inputs are less than the carbon outputs. The cattle tracks in the GR increase the bulk density of the soil thereby discouraging shoot emergence and encourage surface runoff. The area experiences high erosion rates (Maina *et al*., 2013; Khalif, 2015) which selectively carry away the SOC from the surface (Lal, 2008; Were *et al*., 2015). A study done in Northern China on degraded grasslands showed that there was up to a 50% loss of SOC due to exposure of the surface resulting from land use change and overgrazing. This is contrary to a research done by Franzluebbers *et al*. (2000) which showed that grasslands have higher capacity to store SOC than SH, however in this area there was controlled grazing. Differences were seen down the profile as TOC was higher in 0-15cm than in 15-30cm. This can be attributed to higher inputs of litter in the surface compared to the sub-surface. There is minimal rainfall in Suswa which discourages movement of carbon to the lower horizons (O'Brien *et al*., 1978).

The lower TOC in GR compared to SH may be attributed to the distribution of plant root systems in which Jobaggy and Jackson (2000) suggest has more influence on soil organic matter than climate. The plant function types influence the vertical distribution of SOC within the profile (Jackson *et al*., 1996), where grasses have a shallow root profile while shrubs have a deeper root profile. This can explain the higher TOC in SH and lower in GR in the sub-surface horizon. The presence of shrub roots in the lower horizons increases the TOC concentration with root exudates, microbial soil biomass and dehydrogenase activity (Cao *et al*., 2015; Lalitha *et al*., 2016).

In shrubland, POC was the highest (Figure 4.1) which can be attributed to higher litter deposits which have higher labile carbon (Laik *et al*., 2009; Barreto *et al*., 2011) that encourages microbial action. The shrubland in the catchment was fenced, which regulated grazing and disturbance by both livestock and wildlife, moreover, the area has several physical soil management structures to reduce soil erosion. Similar results were found in the Central Himalayan region by Kalambukattu *et al*. (2013), who showed that undisturbed land use types had higher POC due to accumulation of carbon that are protected by soil aggregates.

Agricultural land had lower POC than SH (Figure 4.1), and this is attributable to labile carbon that is highly sensitive to management practices (Kapkiyai *et al*., 1999). Cultivation breaks down protective macroaggregates that expose the POC to higher rates of decomposition and mineralization. The breakdown of the aggregates facilitates oxygenation and hydration of previously protected organic matter and exposes it to decomposers and their enzymes. The concentration of POC in cultivated areas is mainly affected by tillage practices (Bayer *et al*., 2006). A study done by Six *et al*. (1998) to compare conventional tillage and no-till showed that POC decreased in the conventional tillage and increased in the no-till management. The study argued that the breakdown of macro-aggregates and diminished binding agents led to release of labile carbon to a free state; this in turn increases its loss substantially from soil through water erosion. In a similar study, Jacinthe *et al*. (2004) concluded that farms with minimal cover on the soil in between seasons lost higher concentrations of labile carbon compared to those with cover.

Grasslands recorded low POC levels which were not significantly different from the BL (Figure 4.1). These results are similar to those obtained by Cao *et al*. (2013) in the desert steppe in Mongolia, which reflected low POC concentrations in medium and high intensive grazing management systems in China. This was attributed to low surface cover, low root biomass and the vulnerability of the soil to erosion. Herbivore influence on POC in soil is also reflected on selective harvesting of above ground biomass. Li *et al*. (2015) reported that over extraction of green succulent herbage with little input leads to low POC, and suggested that controlled grazing triggers enzymes that increase microbial activities leading to mineralization in the short term. Derner *et al*. (1997) working in the grasslands of Northern Great Plains showed that different grazing regimes influenced plant species diversity, which showed significant correlation with high turnover carbon thereby influencing particulate organic carbon. The results indicate that high grazing intensity resulted in increased competition for POC, therefore reduced labile carbon.

Due to exposure of the soil surface by overgrazing and patches of bareland, the erosion process influenced the lateral carbon fluxes in each land use (Berhe *et al*., 2007, 2012; Hoffmann *et al*., 2013). The POC showed to be significantly lower in all the land use types compared to the mineral organic matter. This may be attributed to light sand size fractions that are easily carried away by water erosion (Lal, 2005). Furthermore, POC does not form organo-complexes with minerals therefore making it susceptible to mineralization (Christensen, 1992). Comparable results were observed in woodlands of Tanzania where enrichment of POC to the total was lower than that of the stable or the silt-clay organic fractions (Solomon *et al*., 2000).The mineral organic carbon was higher than POC and varied significantly across all the land use types indicating that it has a higher reservoir in the soil. These results (Figure 4.1) are in agreement with those of Datta *et al*. (2015) which showed that the recalcitrant material showed minimal decrease across different land use types in sodic soils in India. This is associated with the inaccessibility of MOC due to strong bonds created between the clay surfaces and the soil organic carbon. Similar to the catchment, Yu *et al*. (2017) study on an agro-pastoral land in Northern China showed that MOC changes were negligible and this was due to low oxidation of the recalcitrant material. Other studies have shown that MOC is more sensitive to land use management and is particularly prone to soil erosion due to its association with clay particles which are mobilized entirely by runoff water (Nyawade *et al*. (2016). While Sphon and Giani (2011) observed in Northern Germany that MOC was more sensitive to land use change compared to TOC.

4.4.2 Carbon management index

The carbon EN_{POC} is highest in SH and lowest in BL as shown in Table 4.2. The CMI was highest in AG and lowest in BL. In this study, SH was taken to be the reference land use type.

Table 4.1 Effects of land use types on carbon management index at different depths

	0-15 cm				15-30cm			
	EN_{POC} %	CPI	LI	CMI	EN_{POC} %	CPI	LI	CMI
BL	19.97a	0.34a	0.80a	31.00a	17.00a	0.36a	0.59a	22.77a
GR	23.95a	0.46b	0.81a	41.00ab	17.40a	0.46a	0.64ab	28.93a
AG	27.03c	0.64c	0.82a	53.00b	22.37b	0.68a	0.70c	65.73b
SH	34.99d	1.00d	1.00a	100c	27.30b	1.00c	1.00c	100c

GR-grasslands; SH- Shrublands; AG- Agricultural lands; BL- Barelands. EN_{POC}- enrichment ratio of POC to TOC. CPI- carbon pool index; LI -lability index; CMI- carbon management index. Means with different letters down the column are statistically different. SH is the reference land use type.

The EN_{POC} was highest in SH (34.99%) which was significantly different from the other LUTs. Barelands recorded the lowest EN_{POC} of 19.97% followed by GR at 23.95% and AG at 27.03% at 0-15 cm depth. In the sub-surface, the EN_{POC} were lower than the surface layer.

Shrubland had the highest EN_{POC} at 27.30% which was significantly different from AG (22.37%), GR (17.40%) and BL (17%). The CMI was highest in AG followed by GR then the least was BL (53%. 41% and 31%) respectively in the surface layer. At 15-30 cm, the trend was similar with AG (65.73%) > GR (28.93%) > BL (22.77%) with AG being significantly different from both GR and BL.

For EN_{POC}, SH registered the highest values (Table 4.1). This is because SH provided a less oxidative environment for POC breakdown, due to the presence of the thicket canopy, protective structure of the macroaggregates and lower erodability enabling POC build-up. These results are similar to those obtained by Blair *et al.* (1995) that showed low disturbance in native grasslands increased the lability of carbon to TOC. Similarly, in Brazil, Guareschi *et al.* (2013) evaluated no- till management system and compared it to a native pasture land with minimum disturbance. The results illustrated that higher EN_{POC} was recorded in the enclosed pastures similar to those with no-till of up to 20 years. The lower levels of EN_{POC}, CPI and LI in GR indicate that this land use type is at a more advanced stage of degradation compared to AG which has been under cultivation for the last 7 years (Maina *et al*., 2013). This translates to lower C inputs and higher turnover rates due to high temperature as well as SOC erosion. Similar results have been obtained by Rangel *et al*. (2008) and Cao *et al*. (2013).

The high CMI values in AG may be linked to the use of fertilizer on the farms. The use of nitrogen based fertilizer has been shown to increase SOM and also the presence of crop residues improves the lignin and cellulose content within the surface layer of the soil. These results are comparable to Vieira *et al*. (2007) who showed that in corn cropping systems, addition of fertilizer and stubble increases the lability of SOM by 12% - 46% therefore increasing CMI. Dieckow (2006) also showed that intercropping with leguminous crops could increase the CMI, similar to the farms in Olesharo catchment which have maize and beans intercrop (Maina *et al*., 2013, Ruto *et al*., 2015).

In grasslands, the CMI was lower than that of AG (Table 4.1) which is in contrast to other research studies (Shang and Tiessen, 1997; Silva *et al*., 2004). This is attributable to high herbaceous fine root biomass (Liu *et al*., 2014) that increases the lability of SOC and consequently the CMI. However, due to the rate of grazing intensity, which affects the carbon input fluxes, the CMI was low. There is no definite standard for CMI as it is based on the native land use of an area; however Blair *et al*. (1995) suggested that higher CMI values indicate rehabilitation of carbon while lower CMI values show that the C is being degraded.

4.5 Conclusions and recommendations

This study shows that different land use types have an influence on soil organic carbon pools and consequently the carbon management index. The labile fraction was low across all the land use types and at different soil depths indicating that the labile fraction is easily affected by land use management. Shrublands had the highest POC value which may be attributed to higher litter input and low soil disturbance compared to the other LUTs. The levels of POC in AG were related to the use of fertilizer and intercropping that is practised in the catchment. In grasslands the unexpectedly lower POC levels are linked to the high levels of over grazing leading to low herbaceous litter input. The MOC was higher than the POC due to the fact that it is not easily influenced by soil management systems. In order to assess the sensitivity of the POC to LUTs, the CMI showed that level of degradation in the GR was as severe as that of BL. Therefore efforts aimed at improving SOM within each land use types will improve the soil quality and reverse degradation within the catchment. The study recommends immediate action on the grazing management strategies to reduce above ground biomass harvesting to encourage build-up of SOC. Soil management strategies should be employed in the agricultural areas to increase the labile pool consequently improve the long term fertility of the soils.

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CHAPTER FIVE

Soil Organic carbon and Sediment loss in relation to Gully erosion Olesharo Catchment, Narok County, Kenya

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5.1 Abstract

The study, carried out in Olesharo Catchment, Kenya estimated the total sediment and total SOC lost from the gully channel. The study involved measurement of gully dimensions at selected points with a difference of 5m apart. Averages of upper width, lower width, length and depth were taken to calculate the gully volume. The volume of the gully was used to estimate the total sediment volume and consequently the SOC lost through water erosion. Soil profile pits were dug next to selected points at the right channel, left channel, main channel and sediment areas to determine the soil organic density. Descriptive statistics and Anova were used for data analysis. The results showed the total sediment lost was 313748.71 tons. The right channel had significantly higher SOC at the surface layer of 2.26 kg m^{-3} compared to the other channels and the sediment area at $p < 0.05$. The SOC decreases down the profile in the right and the left channel; however in the main channel, the sub surface layer (1.07 kg m^{-3}) is significantly higher than the surface layer (0.29 kg m^{-3}). In the sediment area SOC increased down the profile with 60-110 cm being significantly higher at 2.24 kg m^{-3} than the SOC in the other channels. Regression analyses revealed that there was a significant relationship between gully dimensions and total soil loss. The study demonstrates the importance of sediment load monitoring and the role erosion plays in carbon loss and sequestration.

Key words: soil erosion, gully, soil carbon, Olesharo catchment

5.2 Introduction

About 85% of the world's degradation is linked to soil erosion (Oldeman *et al*., 1990). It involves the sequential movement of surface soil from one area to a depressional site by a physical agent like wind or water (Lal, 2003). The natural geological process of erosion is important as it is responsible for shaping the earth as it is now (Olson *et al*. 2016); however the accelerated process is a consequent of deleterious anthropogenic activities. The dynamism of land use and cover changes and demographic pressure in the drylands, has led to a shift in the traditional enterprises to adopted activities as commercial complements and shift in land tenure (Tsegaye *et al*., 2010; Kimiti *et al*., 2016). Historically, the effects of erosion are prominent with increasing low fertility, development of gullies that damage infrastructure and reduce soil mobility (Pimentel, 2006).

Concurrent with the need for food security and mitigation of climate change, an understanding the edaphic implications of soil erosion is important. The loss of soil fertility of semi-arid areas due to soil erosion are primarily due to loss of soil organic carbon (SOC) that is preferentially removed due to its light density (Liu *et al*., 2003). Moreover, it is estimated that water erosion moves about 1-5 Pg (1 Pg = 1g $x10^{15}$) of soil carbon annually (McCarty and Ritchie, 2002). According to Morgan (2009), eroded soils lose approximately 75 - 80% of their carbon content with consequent emissions of carbon dioxide (CO_2) to the atmosphere. Water erosion is a four step process from detachment, breakdown of aggregates, transport and deposition in which SOC chemically, biologically and physically is affected

(Jacinthe and Lal, 2009). The stable aggregates are broken down during the detachment and transport process, exposing the SOC to accelerated mineralization (Polyakov and Lal, 2004; Young *et al*., 2014). Consequently, there is deterioration of soil structure, reduced microbial population and development of soil seals and crusts exacerbating the situation further (Gachene *et al*, 2001).

Lateral redistribution of SOC across a landscape by erosion has become popular recently due to the discussion as to whether this geomorphic process is a source or a sink of SOM. Typical researches show that erosion act as source of SOM loss through the exposure to decomposition mechanisms by aggregate breakdown and shear forces (Schlesinger, 1995; Starr *et al*., 2001; Jacinthe *et al*., 2004; Lal, 2004). If the enrichment ratio (ratio of C in sediments carried by water to the C in the original soil) is greater than unity, then it's considered a source. However, recent studies have shown that, burial of carbon by soil layers leading to its protection from mineralization is considered a sink as long as it's within the same watershed area (Smith *et al*., 2004; Quine and Van Oost, 2007; Olson *et al*., 2016). Carbon sequestration is calculated by monitoring carbon fluxes from eroding sites and depositional areas with estimates of about 1.5 Pg C yr $^{-1}$ (Stallard *et al*., 1998; Berhe *et al*., 2007).

Olesharo catchment is predominantly steep sloped with a network of gullies that run from the high elevation areas to the lower areas (Maina *et al*., 2013; Khalif *et al*., 2015). Recent research has linked gully erosion to high sediment production that ranges from 50 – 80% at the depositional areas (Valentin and Poesen, 2005). This has led to severe impact on loss of fertility upslope and burial of vegetation as well as destruction of infrastructure downslope (Chaplot *et al*., 2005). Although there are no agreeable standard dimensions of a gully, the conclusive idea is that it is a linear incision caused by intermittent flow in erodible soils that cause steep sided tunnels which interfere with normal tillage practices and surface flow (Poesen *et al*., 2003; Torri and Borselli, 2003; Brady and Weil, 2008).

Considered the worst stage of water erosion, 29 million ha in Africa is said to be affected by gully erosion and with a total of 16-300 t ha^{-1} yr^{-1} in Ethiopia which is considered to experience the highest erosion rates in the East African region (Torri and Borselli, 2003; Pathak *et al*., 2005). There are distinct on-site and off-site effects of gully erosion within a catchment which include reduce effective soil depth, restriction of infiltrated moisture, shrinkage of farm sizes, animal and human movement restriction and adversely affects agricultural activities (Casali and Giraldez, 1999; Sirvio *et al*., 2004; Yitbarek *et al*., 2012). Total sediment lost has been calculated from gullies through various way including field survey methods, test plots and alternative erosion models like RUSLE and direct measurement of gulley dimensions to estimate the volume translates to the total amount of soil loss within a channel (Angima *et al*., 2003; Casali *et al*., 2006; Nasri *et al*., 2008; Tarakegn, 2012).

Field investigations have been limited to a plot scale; therefore studies at a catchment scale are important in the understanding of gully erosion. Moreover, there are fewer studies on gullies in non-agricultural landscapes as there are for agroecosystems. The objective of this study is to estimate how much total sediment lost has been carried away through its volume and consequently calculate how much SOC has been lost by the gully. Information generated from this study will be used for soil water conservation in degraded areas and influence on climate change mitigation strategies.

5.3 Materials and Methods

5.3.1 Description of study site

Find the study description in chapter three

5.3.2 Suswa soils

Find the Suswa soil descriptions in chapter three

5.3.3 Olesharo Gully

The figure (5.1) shows the extent of the Olesharo Suswa gully.

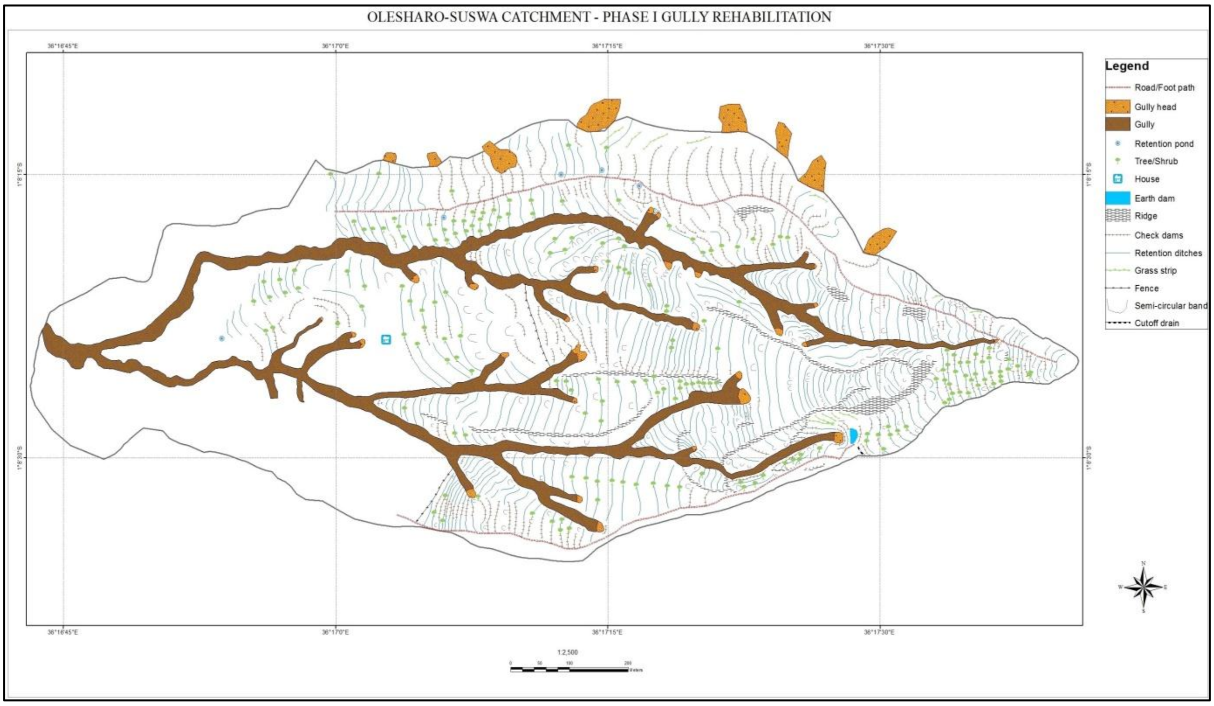

Figure 5.1 Cartographic figure showing the extent of the Olesharo Gully. Catchment area indicating the distribution of different gully control and rehabilitation structures. SLM project, 2015

The Suswa hill is dominated by an intricate network of deep gullies (Khalif *et al*. 2015). Geomorphologically, there are pronounced cattle tracks evidence of intense runoff and flash floods during the rains (Odini *et al*., 2015).The area is dominated by scattered acacia tree species and *Thaconathusz camphoratus* which is an indication of dry weather conditions and depressed rainfall amounts (Reed *et al*.,2009). On the right channel of the gully, the main land use type is rehabilitated shrubland, the left channel is the degraded shrubland and the main channel is found on the lower part of the catchment predominated by grasslands, patches of bareland and agricultural lands.

5.3.4 Sampling Design and Soil Sampling

Undisturbed soil samples were collected from the gully sides at three locations of the gully that show the soil profiles. Profile pits were dug close to the edge of the gully and samples were collected. Using a core ring of known volume, samples were collected to calculate the SOC density within identified horizons 0-15 cm, 15-30 cm, 30-60 cm and 60-110 cm. Additional rings were taken to calculate the mean bulk density of each horizon using cylindrical core rings of 5 cm dimensions. The SOC densities (kg m^{-3}) were then used to calculate the total SOC that has been lost through erosion using the gully dimensions. At the sediment area, disturbed soil samples were collected from three locations from depth 0-15cm, 15-30 cm, 30-60 cm and 60-110cm.

5.5.5 Gully dimensions

There are five main gullies that cut across the landscape; therefore the focus was on the main one that extends up to the town. Gully volume was determined from the cross sectional area of the gully and the length between gully segments. The cross sectional area was determined by measuring the cross section of the gullies. The coordinates of the gully was determined with a hand held Garmin Etrex global positions system (GPS) receiver (Garmin International, Inc., Olathe, Kansas) with 2m accuracy.

The mean dimensions were calculated to estimate the average gully volume

$$\text{Average width} = \frac{WT+WM+WB}{3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{Eq1}$$

Where, WT= Top width, WM=Middle width, WB = Bottom width

Average height $\sum_{H=0}^{\infty} \frac{(H1+H2+H3+H4+..Hn)}{N}$……………………….Eq 2

Where H is the height of the gully

To calculate the gully volume;

Volume earthworks = ½ (A+B) H x L**………………………..**Eq 3

A= upper width of the gully

B= lower width of the gully

H= average Height

L=Length

This will represent the total sediment loss from the gully (Munoz Robles *et al*., 2010; Tarakegn, 2012).

5.3.6 Physical and Chemical Soil Analysis

The soil samples were air-dried, ground and sieved through a 2 mm sieve to remove any visible plant residues. Concentration of SOC was estimated through the Walkley-Black wet oxidation method (Nelson and Sommers 1982. For bulk density, the samples in the core rings were oven dried at 105°C for the standard 48 hours. (Blake, 1965), and determined by dividing the weight of the dry soil by volume of the core rings. Soil texture was determined through the hydrometer method after dispersing soil with sodium hexa-metaphosphate solution to eliminate organic matter (Day, 1956).

5.3.7 Estimation of Soil Organic Carbon density

The SOC density were calculated using the equation

$$SOCd = BDjth * 1000 * \frac{SOC}{1000} \text{.............................Eq 4}$$

Where: SOC_d is SOC density of jth horizon (kg m^{-3}); BDjth mean bulk density of the jth horizon (g cm^{-3}) which is multiplied by 1000 to change it to kg m^{-3} and SOC mean content of SOC concentration of the jth horizon divided by 1000 to change it to (g kg^{-1}) (Meersmans *et al*., 2008; Han *et al*., 2010).

5.3.8 Total amount of organic carbon lost from the gully

To calculate the total amount of SOC lost from the gully, weigh the SOCdj to the thickness of each horizon to give stocks. The stocks are added for each horizon to get the total stock in each channel down the soil profile. A summation of SOC stocks modified equation from Were *et al*. (2015)

$$SOC\ total\ stock = \sum_{j=1}^{n} \frac{SOCjth}{100} \times BDjth \times Djth \times 100 \ldots\ldots\ldots\ldots.Eq\ 5$$

SOC total stock is the soil organic carbon stock (Mg C ha^{-1}); SOC jth is the soil organic carbon concentration (%) in the horizon, which is then converted to g C g^{-1} soil; BDjth is the bulk density (g cm^{-3}) in the horizon; BDjth is the depth (cm) of the horizon; which we multiply by 100 to change from g C / cm^2 to Mg C /ha^{-1}.

Total SOC in the gully lost from the soil profile is

$$SOC\ g.total = (Wa * H * L * SOCtotalstock\ ) \text{ ....Eq 6}$$

Where SOC g. total (Kg m^{-3}) is the total soil organic carbon lost from the gully, Wa (m) is the average width; H (m) is the height of the soil profile from which the horizons were taken; L (m) is the length of the channel.

5.3.9 statistical Analysis

Analysis of variance (ANOVA) and Duncan's multiple range test (DMRT) for comparison of means were performed using software SAS 9.1.3.The statistical significance was determined at $P < 0.05$.

5.4 Results and discussion

5.4.1 Total sediment lost

Table 5.1 shows the total volume within the gullies. The gully has three channels; left channel and right channel which feed into the main channel.

Table 5.1 Descriptive statistics of Olesharo gully dimensions

Gulley dimensions	Left channel	Right channel	Main channel	
Upper width (m)	8.61	10.17	13.8	
Lower width (m)	4.66	4.94	8.11	
Average depth (m)	5.43	6.23	5	
WDR	1.22	1.21	2.19	
CA (m^2)	36.03	47.07	54.78	
Length (m)	1.5×10^3	1.7×10^3	2.7×10^3	
Total volume (m3)	54001.35	80015.01	147858.75	281875.11
Total soil loss (tons[a])	55621.39	82175.41	175951.91	313748.71

[a]Calculated using 1.104 g cm^{-3} bulk density for non-recently cultivated surface mineral soils. WDR- width depth ratio, CA- cross-section area.

The average upper width of the main channel is 13.8m which is the highest. The right channel is 10.17m while the left channel is 8.61 m. The lower width is lower across the three channels. The average depth of the gulley from the upper slope to the lower slope ranges from 5.0 m to 6.23 m. The WDR for the main channel is 2.19 followed by the left channel (1.22) then the right channel (1.21). The main channel extends the longest to 2.7 x 10^3 while the shortest is left channel at 1.50 x 10^3. The total soil loss in m^3 is 281,875.105 and in tons is 313748.7131.

According to the FAO (1977) scaling of types of gullies, the left and the right channel are of medium size (Table 5.1). This is because the FAO solely categorises the gully based on depth where $D > 5$ m is considered to be large, $1 > D < 5$ m is medium size and $D < 1$ m is considered a small gully. However this may not be sufficiently adequate as the width and length of the gully play a major role in determining how much soil is lost from the gully.

According to a study done in southern Spain, Casali *et al*. (2006) categorised gullies according to Width to depth ratio (WDR) and cross section area (CA) values. Using this scale the WDR < 5 and CA > 0.06 m^2, the channels in this study are considered large, narrow and deep. This is partially agreeable with Poesen *et al*. (2001) whose scale is only dependent on the WDR which describes gullies with WDR greater than 1 as wide and shallow. The left and right gully channels are narrower than the main channel, indicating presence of gully heads and initial stages of the Olesharo gully (Belay and Bewket, 2012). Moreover, the right and the left gully channels are found at higher elevations than the main channel indicating potential higher velocity than at the more gentle slopes. The main gully is shallower than the other channels indicating gently slope which has a constant bed gradient with similar traits to stream gullies which were found by Billi and Dramis (2003).

Using the gully dimensions (width, depth and length), the total amount of sediment lost was 281,875.11 m^3 equivalent to 313,748.7131 tons, which is obtained from multiplying volume by average bulk density of the profile (Landon, 1984). This amount is high compared to Belay and Bewket (2012) findings in north-western highlands of Ethiopia which had similar large gullies with total soil loss of 82,692 tonnes and Australia by Muñoz-Robles *et al.* (2010) where the average sub-catchment lost about 7096 m^3.

5.4.2 Total SOC lost from the gully in the Olesharo Catchment

The highest mean SOC densities are found in the right channel at 0-15 cm depth while the lowest is in the main channel from 60-110 cm

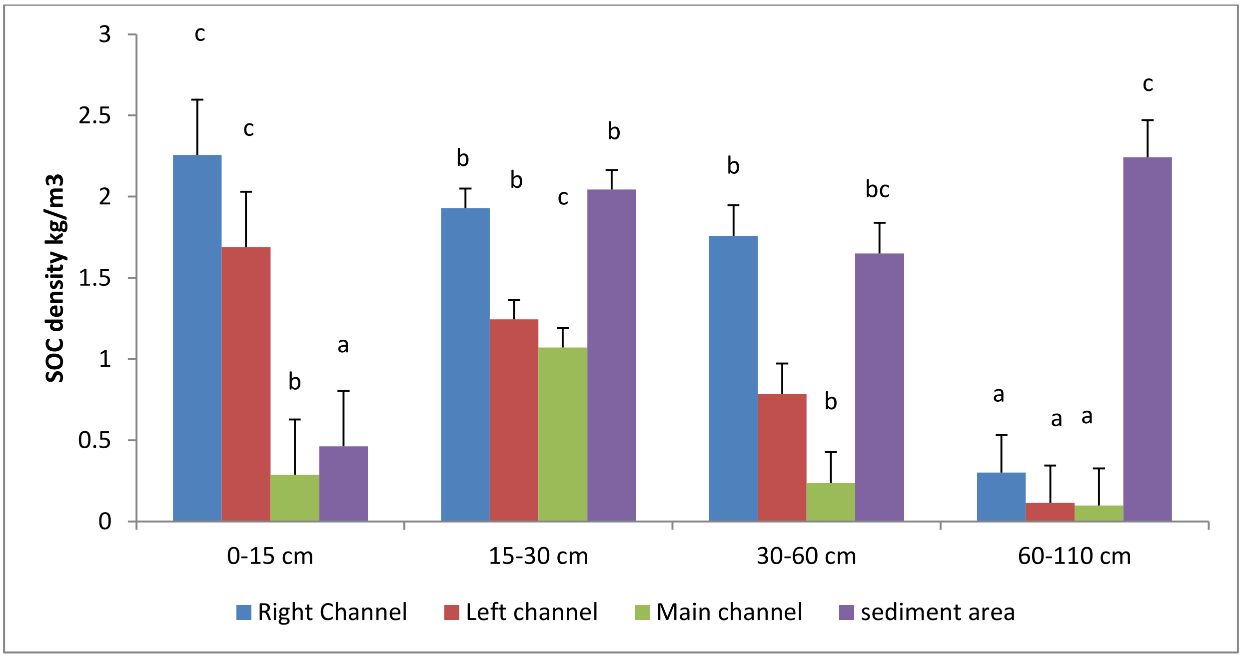

Figure 5.2 Mean SOC density in each channel at different depths down the profile.

The highest mean total SOC density is found in the right channel (2.26 kg m^{-3}) followed by 1.69 kg m^{-3} in the left channel, depositional area (0.46 kg m^{-3}) and the least is the main channel (0.27 kg m^{-3})in the 0-15cm. The right channel recorded the highest at 15- 30 cm and 30- 60 cm, (1.93kg m^{-3} and 1.75 kg m^{-3} respectively). In the 60-110 cm, the sediment area has the highest C density with 2.42 kg m^{-3} followed by the right channel at 0.30 kg m^{-3} and the least is main channel with 0.09 kg m^{-3}.The left channel had significantly lower SOC densities than the right channel at 15- 30 cm (1.24 kg m^{-3}), 30- 60 cm (0.78 kg m^{-3}), 60-110cm (0.11 kg m^{-3}). The main channel had the lowest with1.07 kg m^{-3} at 15- 30 cm, 0.24 kg m^{-3} at 30- 60 cm and 0.09 kg m^{-3} at 60-110 cm. In the right and in the left channel, SOC decreased with soil depth, while in the main channel, the 15- 30 cm had higher SOC density compared to the surface layer. In the sediment layer, the SOC increases down the profile.

The high SOC density in the right channel down may be due to the shrublands surrounding the area, which has been rehabilitated for the last four years. The area has been enclosed to regulate grazing and to control gully erosion. The slope is dominated by check dams, cut of drains and re-vegetated retention ditches to regulated soil and water movement down the profile. These measures have been seen to control soil erosion rate, encourage water infiltration which improves above ground biomass consequently improving litter that increases SOC density. Similar studies that have used enclosure system in the drylands to improve soil properties are popular in Kenya; for instance in West Pokot, where Mureithi *et al*. (2014) showed an absolute increase in SOC and decrease in bulk density. The enclosed area may have higher moisture content, improved litter quantity and quality and balanced carbon fluxes that encourage SOC build-up (Sanjari *et al*., 2008; Park *et al*., 2013).

In the left channel, the SOC was seen to be lower than the right channel. This may be because it is an open area, for communal grazing. The steepness of the slope coupled with non-existent soil erosion measures has reduced the SOC content in the soil. The main channel has considerable low SOC which may be attributed to the landuse in the area which is degraded grasslands, agricultural land and patches of bareland. The gully dimensions of the main channel (higher WDR) imply higher soil loss consequently higher SOC loss. Olson *et al*. (2011) records, within an agricultural landscape, a loss of up to 48% of the original SOC over a 150 year period when compared to the adjacent native woodland due to poor tillage practices. The SOC expectedly decreased down the profile in all the channels except the main channel where the sub surface layer had significantly higher SOC than the 0-15 cm. This can be attributed to the intensive degradation on the surface in the land use adjacent to the gully at this position. The grasslands have been degraded due to overgrazing consequently exposing the soil to mineralization of SOC. Soil organic matter decreases due to low inputs of C through litter fall or leaching down the profile (Liu *et al*., 2003).

In the depositional area, the SOC was unexpectedly lower in the upper horizons as compared to the gully channels. This may be due to the burial of top productive soil by multiple layers of sediment (mainly loose pumiceous materials) with low amounts of SOC. Therefore the upper layers of the sediment areas have lower SOC than the underlying. Similarly, a study done by Liu *et al*. (2003) described the burial of the top fertile layers by the sub-surface layers protected the SOC from mineralization. He concluded that erosion and deposition can act as a sink in croplands reducing the release of CO2 to the atmosphere. In a similar study by Berhe *et al*. (2007), their results argued that the higher content of C in the lower horizons within sediment areas was because of low oxygen and higher moisture content during deposition which lowered decomposition rates. Furthermore, Sanderman and Amundson (2003) argued that during the transport and deposition process, new aggregates are formed around the SOC, such that mineralization during burial at depositional areas is reduced.

Table 5.2 Total soil organic carbon loss from the Olesharo gully

The total SOC loss was estimated to be 184,495.59 kg from the right channel, followed by the main channel with 104,991.55 kg and finally the left channel with 80,121.12 kg.

	Total SOCst (kg/ ha)	Total soil volume profile m^3	Total SOC lost (kg)	TOTAL (kg)
Right Channel	130590	14127.85	184,495.59	
left channel	73185	10947.75	80,121.12	
main channel	32269	32536.35	104,991.55	
Total				369,605.43

The total SOCst was calculated by the summation of the SOC in the horizons per channel. The highest was 130,590 kg followed by left channel and main channel (73183 kg, 32269 kg respectively). The total soil volume down the profile in each channel was obtained by multiplying the dimensions with the height at 110 cm since this is the depth of the soil profile. The total volume was highest in the main channel with 32536.35 m^3 followed by the right channel 14127.85 m^3. The lowest was the left channel with 10947.75 m^3. The total volume of SOC lost from the entire soil profile in Olesharo gully was summed to 369,605.43 kgs.

The stocks obtained from each horizon were added and used to calculate the total amount of SOC stored within each profile in each channel. The ratio between the total SOC lost by the gully to the total amount of sediment lost from the gully is 1.3, this falls close to the range provided by Lal (2003) of between 0.8-1.2 for Africa which induces 20% loss of CO_2 due to mineralization during the detachment, transport and deposition. This study recorded a total of 369,605.43 kgs (approximately 370 tons) loss of SOC which is higher than other sites in similar AEZs in Kenya. In Taita hills in the southern part of Kenya, Sirvio and Rebeiro-

Hargrave (2004) recorded a distinct low soil fertility index which is attributable to loss of SOM in the different gully positions. Olson (2016) argued it is important to identify the different areas of measurement along the watershed, since there are eroding sites, transport sites and depositional sites and each has different levels of SOC. In the erosion sites of an erosion prone mixed land use type area, the total soil loss was 134 Mg (134.3 tonnes) of soil eroded from the catchment in the prairies of Northern America. This is considerably lower than that in the Olesharo catchment, which can be attributed to the area differences covered by the catchments and the gully dimensions.

The influence of land use on gully development is important in understanding the SOC concentrations in the different gully profiles within the catchment. A study in New Zealand by Gomez *et al*. (2003) showed that there was a 138% increase of gully area due to change of grasslands to farmlands over a period of 41 years. Similarly, Marden *et al*. (2012) showed that revegetation of an island in north of New Zealand restricted gully hydrology therefore controlling total soil loss.

5.5 Conclusion and Recommendations

The study attempts to elucidate the adverse effects of gully erosion through calculation of total sediment loss and total SOC lost from the catchment. The results show there is a significant loss of soil from the gullies and total SOC in kgs. The high SOC in the right channel is attributed to the proximity to enclosed shrublands, which have a higher content of SOC compared to the adjacent degraded grasslands. This explains the role of land use, its management and rehabilitation of land on SOC within a catchment. There was significant decrease of SOC down the soil profile in the channels, with 60-110cm containing the least. The low SOC in the upper layers of the depositional sites and its consequent increase in depth, attempts to explain the role of erosion and deposition as a carbon sink. The study highlights the importance of monitoring the loss of SOC so as to maintain the losses within the threshold limits out of which prevents recovery from degradation in the gullied environment.

The study recommends the assessment of the rate of soil loss within the gullies so as to predict how much soil the gullies would lose in the future. Furthermore, there is need to set up soil erosion measures on each gully channel (physical and vegetative) to reduce future soil and carbon losses within the Olesharo Catchment.

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CHAPTER SIX

GENERAL CONCLUSION AND RECOMMENATION

6.1 Conclusion

The study assessed the impacts of LULCC on soil quality as an indicator for soil degradation. The results show that SOC and TN stocks vary depending on land use/ cover type. The shrublands of the Olesharo catchment had the highest SOC stocks while GR and BL had the lowest. This may be attributed to the high content of litter which is allowed to accumulate due to land use practised by the community. Agricultural land also had higher carbon stocks which may be due to minimum tillage practices and use of animal manure on farm to grow crops. The farmers practice intercropping and leave crop stubble after harvest which is a sustainable practice. Grasslands however had low SOC stocks due to high intensity grazing that is predominant in the catchment. There was high bulk density and lower C/N ratios in the GR and BL indicating low subsurface moisture holding capacity and low microbial biomass. The low above ground biomass discouraged carbon accumulation through higher rate of mineralization of SOC and TN due to exposed surface layers to high temperatures. This study provides a basis on the potential of land use types to protect soil and store carbon as a strategy for climate change mitigation.

Further the study sought to assess land degradation through SOC pools in each land use/ cover type. The labile fraction represented by POC was the lowest in all the LUTs, concluding that it was the most sensitive to land use change. There was significant difference across all the land use types and depths meaning it is the best early indicator of degradation compared to TOC and MOC. In GR, the POC was low, showing that low herbaceous cover as a result of overgrazing reduces the lability of soil organic matter. The carbon management index for agriculture was higher than that of GR which is an indicator that grasslands were as degraded as barelands.

Finally, the study attempts to assess the impact of gully development on soil organic carbon and total sediment loss within the catchment. The main gully found in the catchment had three channels, the left, right and the main one. Both the left and the right were found at higher elevations with a steeper gradient, meaning they were narrow and deep. The main channel was found at gentler slope positions making it shallower that the other two. The total amount of sediment lost was 313,748.71 tons calculated from the gully dimensions. The estimated SOC lost from the gully was high at 369,605 kgs of SOC since the inception of the gully. The right channel which had soil water conservation measures had the highest SOC, which shows how important physical as well as vegetative structures are in SOC build up and storage. This objective concluded the need for constant monitoring of SOC loss and its implication as a carbon source or sink in climate change. Overall, SOC plays a vital role in soil sustainability and potential climate change mitigation strategies.

6.2 Recommendations

The study concluded that SOC is an effective indicator for soil quality. However there is need for further research within the catchment, therefore the study recommends the following:

1. There is need for holistic grazing management in the Olesharo catchment to control the adverse effects of high intensity grazing within the area.
2. Further study should be done to compare different grazing intensities on SOC stocks and pools, site specific information and profile attributes within each land use type.
3. Prediction studies on SOC changes within different land uses should be estimated including the SOC lost from the gully.

4. There is need for calculation of erosion rate from the gully network in the catchment to predict future losses of sediments.

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APPENDICES

Appendix 1: Soil texture under different land use types under different depths

	0-15 cm			15-30 cm		
	SAND%	CLAY%	SILT%	SAND%	CLAY%	SILT%
GR	66.59b	11.57a	21.83a	64.76a	12.65a	22.59a
SH	74.32c	8.52a	17.16a	73.99b	8.23a	17.78a
AG	61.73a	14.91a	23.36a	61.02a	14.67a	24.31a
BL	65.43b	11.54a	23.03a	64.34a	11.78a	23.88a

Appendix 2: soil bulk density under different land use types at different depths

	SH	AG	GR	BL
0-15 cm	1.014a	1.091ab	1.111ab	1.123b
15-30cm	1.021a	1.045a	1.046a	1.117b

Appendix 3: Pearson's correlation coefficients between soil textures and selected soil parameters at different depths

	0-15cm						15-30cm					
Soil Parameters	SOC	TN	BD	SAND	CLAY	SILT	SOC	TN	BD	SAND	CLAY	SILT
SAND	-0.42*	-0.48*	0.1	1	0.52*	-0.47*	0.21	0.21	-0.1	1	-0.32	-0.52
CLAY	0.31	0.39	-0.04	-0.45*	1	0.86**	0.21	0.14	-0.13	-0.32	1	0.86**
SILT	0.43*	0.41	-0.021	-0.61**	0.86**	1	-0.31	-0.08	0.24	-0.52*	0.86**	1