Relationship between Vegetation Cover Types and Soil Organic Carbon in the Rangelands of Northern Kenya

Submitted by

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DECLARATION

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ABSTRACT

Accurate and reliable estimates of soil organic carbon stocks (SOCS) in the rangelands are critical for the development of effective policies and strategies to mitigate the effects of climate change resulting from increasing atmospheric concentrations of carbon dioxide (CO_2) and greenhouse gases (GHGs). Rangelands of northern Kenya are characterized by a patchy vegetation covers that is linked to high rainfall variability, both spatial and temporal, and soil characteristics as well as frequent droughts that have aggravated the decline of the already fragile ecosystem, leading to reduction of soil organic carbon (SOC) and its spatial variability within the rangeland. The wider objective of the current study was to estimate the relationship between vegetation cover types and SOCS. A Landsat 5 Thematic Mapper (TM) satellite image of spatial resolution of 30 x 30 m was used to map and differentiate vegetation into different cover types. A transect of 750 m was laid across each vegetation cover type and soil samples taken at intervals of 50 m at a depth of 0-15cm (n=60) for SOC concentration determination, soil bulk density (g cm^{-3}) and computation of SOCS. The SOC concentration was determined using the colourimetric method (wet-oxidation with potassium dichromate) while the soil bulk density was done by core sampling method The values of Normalized Vegetation Index (NDVI) and Soil Adjusted Vegetation Index (SAVI) were derived from Landsat 5 TM satellite data. One way analysis of variance (ANOVA) and simple linear regression model was used in the statistical analyses. Four vegetation cover types were indentified, bare land (BRL), sparsely distributed acacia with bare ground (SAB), sparsely distributed acacia with a forb (SAF) and Acacia bushland (ABL). The means of SOC concentrations (%) for each vegetation cover type were different (BRL, 0.18±0.05; SAB, 0.28±0.07; SAF, 0.47±0.04; ABL, 0.59±0.14) with an overall mean 0.38±0.18% ($P<0.5$), while those of soil bulk densities (g cm^{-3}) were (BRL, 1.32±0.08; SAB, 1.23±0.14; SAF, 1.14±0.10; ABL, 1.15±0.10) with an overall mean of

1.23±0.14. Soil bulk densities under BRL and SAB were similar but different from that of ABL and SAF that were alike ($P<0.05$).

Separate means of SOCS (t C ha^{-1}) were (BRL, 3.53±0.79; SAB, 5.42±1.51; SAF, 8.23±0.97; ABL, 10.05±2.02) for each vegetation cover type with an overall mean of 6.76±2.85,($P<0.5$). Positive relationship was established between the average mean values of both NDVI and SAVI when regressed with the average mean values of SOCS ($R^2 = 0.89$) under the four vegetation cover types. Differences in SOCS and SOC concentration between vegetation cover types suggest that there is a fundamental difference in the relative rates of organic incorporation into the soil, chemical composition and carbon cycling processes. This indicates that the spatial variability of SOCS may partly be explained by the type of vegetation cover. Vegetation indices like NDVI and SAVI derived from Landsat 5 TM satellite data can be useful tools to relate SOCS and vegetation cover types in rangelands of northern Kenya.

DEDICATION

This work is dedicated to my late father, Paul Kibirgen Arap Lalang (Chemwor),

and

My mother Rael Lalang

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LIST OF ABBREVIATIONS/ ACRONYMS

ABL	Acacia bushland cover
ACZ	Agro - Climatic Zones
ANOVA	Analysis of variance
ASALs	Arid and semi arid lands
BRL	Bare land
CO_2	Carbon dioxide
CV	Coefficient of variation
DAAD	Deutscher Akademischer Austausch Dienst
DEM	Digital Elevation Model
FAO	Food and Agriculture Organization of the United Nations
g	gram
GEFSOC	Global Environmental Facility project of Soil Organic Carbon
GHG(s)	Greenhouse gas(es)
GIS	Geographical information systems
GoK	Government of Kenya
GPS	Geographical positioning system
HSD	Honestly Significant Difference
H_2SO_4	Sulphuric acid
ID	Identification
ILRI	International Livestock Research Institute
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
KARI	Kenya Agricultural Research Institute
$K_2Cr_2O_7$	Potassium Dichromate
kg	kilogram
Landsat 5 TM	Landsat 5 Thematic Mapper
MDG(s)	Millennium Development Goals

MODIS	Moderate Resolution Imaging Spectroradiometer
NARL	National Agricultural Research Laboratories
NDVI	Normalized Difference Vegetation Index
NPP	Net primary productivity
PgC	Pentagram of carbon (1Pg = 10^{-15} g)
pH	Potential for hydrogen ion concentration
ppmv	parts per million by volume
SAB	Sparsely distributed acacia with bare ground cover
SAF	Sparsely distributed acacia with a forb cover
SAVI	Soil Adjusted Vegetation Index
SIC	Soil inorganic carbon
SOC	Soil organic carbon
SOCS	Soil organic carbon stocks
SOM	Soil organic matter
TgC	Teragram of carbon
UNESCO	United Nations Education, Scientific and Cultural Organization of United Nations
UNFCCC	United Nations Framework Convention on Climate Change

CHAPTER ONE

INTRODUCTION

1. Background information

Globally, atmospheric concentration of CO_2 and other GHGs increased drastically from 280 parts per million by volume (ppmv) in 1750 to 367 ppmv in 1999 (Lal, 2004a) while in 2005, the CO_2 concentration was estimated at 380 ppmv (Houghton, 2007). This enrichment of CO_2 and GHGs has led to an increase in average global surface temperature (Lal, 2004a), resulting in increments of 1-2° C in mean annual temperature in Kenya (ILRI, 2008). Increases in global average temperature exceeding 1.5-2.5°C and atmospheric CO_2 concentration can lead to major changes in ecosystem structure and functions, with predominant negative consequences on biodiversity, and ecosystem goods and services (IPCC, 2007). This potential scenario has made it necessary to concentrate efforts towards the development of strategies to mitigate the threat of global warming. The process of carbon sequestration in soils can be considered as a valuable option to reduce the rate of CO_2 enrichment in the atmosphere (Salahuddin, 2006; Roncoli *et al.,* 2007).

Attempts to estimate the SOCS at global scale as a means of combating global warming has been reported in different studies (e.g., Post *et al.,* 1982; Eswaran *et al.,* 1993; Sombroek *et al.,* 1993; Batjes, 1996). These estimates are based on information derived from different global soil maps and soil carbon concentrations and other attributes obtained from representative soil profiles, resulting to variability in global SOCS estimates (GEFSOC, 2003). Soils contain twice as much carbon as the atmosphere and, approximately three times that of the total terrestrial carbon pool (Batjes, 1996; Lal, 2004a; Li *et al.,* 2010), with arid and semi - arid lands (ASALs) having the lowest SOCS per unit area compared to humid zones (GEFSOC, 2003). However, ASALs are of global importance because they occupy larger areas and have the potential to sequester significant amount of CO_2 from the atmosphere (Lal *et al.*, 2001).

Soil carbon stocks appear in different forms, SOC being the major one (Batjes and Sombroek, 1997). Increase in SOC abundance is beneficial in mitigating the effects of climate change or variability (Batjes, 1994; GEFSOC, 2003). Soil organic carbon is also of local importance as it affects ecosystem and agro-ecosystem functions, by influencing soil fertility, water holding capacity, and other soil chemical and physical properties (Ardö and Olsson, 2002; Rice, 2005). Policies and scientific research concerning carbon cycling depend on existence of accurate information about the spatial distribution of carbon in vegetation and soil components of terrestrial ecosystems (Lufafa *et al.*, 2008). This, in turn, is guided by the Kyoto Protocol (UN, 1998), in which Kenya became Party to by ratifying the UNFCCC in 1994 (GoK, 2002).

Soil organic carbon is sensitive to a range of factors, including climate, topography, soil type, above-ground vegetation properties (stand age, leaf area index, above-ground biomass, mean tree height, tree diameter and stand density), land use change and management (Li *et al.*, 2010). Though there are some studies that have estimated differences in SOC in relation to climate, land use change, topographic aspect and vegetation (e.g., Sombroek *et al.*, 1993; Yimer *et al.*, 2006), few have evaluated relationships between vegetation types and SOCS in the ASALs (e.g., Stavi *et al.*, 2008). This is probably because high spatial variability of SOC in ASALs requires very high sampling densities to get accurate estimates, making it difficult to monitor changes in carbon storage (Bird *et al.*, 2002; Martin *et al.*, 2011). Allen *et al.* (2010) argued that plant material provide the main source of SOC through litter drop, the production of root exudates and root mortalities. Consequently, the size, morphology (e.g., tree, shrub and grass) and spatial distribution of plants can affect spatial distribution of SOCS (Allen *et al.*, 2010). Spatial distribution of SOCS as influenced by vegetation types has not been established in the *'rage'* grazing unit (*rage*) of Kalacha location in Chalbi district of Marsabit County. The current study, therefore, sought to establish the relationship between vegetation cover types and SOCS in this area.

1.1. Statement of the problem

Rangelands of northern Kenya are the main prime drivers of pastoralists' economy. It is an important resource for livestock production as well as carbon sequestration, habitat for wildlife and tourism attraction sites. High rainfall variability, both in space and time, and varying soil properties contribute to vegetation patchiness and also acts as the principal constrains to biomass production. Frequent droughts experienced in the region have aggravated the decline already fragile ecosystem, creating seasonal or permanent plant cover removal that has left the soil surface bare in some parts within the rangeland. This impedes carbon sequestration potential as well as creating spatial distribution of SOCS, which makes it difficult to manage rangelands with an aim of combating the effects of climate change and improving soil quality and, subsequently, ecosystem services. With the impacts of projected climate change of increase in temperature and decrease in effective rainfall, this may further decrease NPP and worsen the situation, leading to further reduction of SOC.

1.2. Objective of the study

The wider objective of this study was to determine the relationship between SOCS and vegetation cover types with a view to contribute to management of rangelands to combat effects of climate change, soil quality improvement and, subsequently, enhance the ecosystem services. To achieve this, and in regard to northern Kenya, the specific objectives were to:

(i) Differentiate vegetation cover types of the ‘*rage*’ grazing unit using satellite imagery and ground-truthing.
(ii) Determine the SOC concentration underneath each vegetation cover type indentified.
(iii) Determine the soil bulk densities underneath each vegetation cover types indentified.
(iv) Relate the SOCS with vegetation indices derived from satellite image.

1.3. Research hypotheses

To achieve the goal of this study, it was hypothesized that;

(i) Different vegetation cover types have different SOC concentrations, soil bulk densities and SOCS.
(ii) Vegetation indices derived from satellite image could be used as tools to relate SOCS and vegetation cover types.

1.4. Justification of the study

Methods of estimating SOCS can be categorized into two; direct measurements of SOC in the field or laboratory, and indirect estimates of carbon stocks and its changes by utilizing remote sensing, geographical information systems (GIS), geostatitics and SOCS simulation models over a specified period of time. Direct methods are very accurate and provide site specific information but they are labour intensive, costly and time consuming. Indirect methods are non-intrusive, low cost and can provide spatially continuous information over a target area on a repetitive basis. Extrapolating SOCS over larger areas using indirect methods depends on the relationship developed at plot level and/ or field scale. The current study aims to estimate the relationship between vegetation cover types and SOCS. Relating vegetation cover types and SOCS levels offers a rapid real time and low cost methodology of estimating SOCS at a local scale, particularly in vast areas that are characterized by heterogeneous patchy vegetation cover.

1.5. Scope and limitation of the study

The present study was conducted in the *'rage'* grazing unit of Gabra rangeland of Kalacha location in Chalbi district (Marsabit County) in northern Kenya for a period of three months. The findings, though specific to the study site, can be extrapolated to other areas but with caution. Due to the high cost of analyzing other soil properties (e.g., soil moisture content, pH, texture and electrical conductivity), apart from SOC concentrations and soil bulk densities, was beyond the capacity of the current study, and are recommended for future research. The prevailing prolonged drought during the field work also influenced the observations of this study. It is, therefore, necessary to undertake a longitudinal study to capture more information on the variables studied.

CHAPTER TWO

LITERATURE REVIEW

2. Overview of rangelands of Kenya

Kenya's land is divided into seven agro-climatic zones (ACZ) based on moisture index (Sambroek *et al.,* 1982) as summarized in Table 1. The term ASALs is used interchangeably with rangelands in this study. These areas represent 80% of the country's total land mass and support 25% of the human population and 50% of the total livestock population (GEFSOC, 2003). The ASALs lie in agro-climatic zones IV, V and VI (GEFSOC, 2003), with an average annual rainfall of less than 200 mm in Chalbi desert, northwest of Marsabit (McPeack, 1999). Due to infertile soils and, low and high variable rainfall, ASALs are ill-suited for intensive crop production but fairly-suited for extensive livestock production (Barret *et al.*, 2003).

Table 1. Agro-climatic zones (ACZ) of Kenya

ACZ	Classification	Moisture index	Historical Natural Vegetation
I	Humid	>80	Forest undifferentiated
II	Sub-humid	65-80	Forest undifferentiated
III	Semi-humid	50-65	Grassland and closed savannah
IV	Semi-humid to semi-arid	40-50	Grassland and open savannah
V	Semi-arid	25-40	Grassland and closed shrubs
VI	Arid	15-25	Open to closed shrubs
VII	Very arid	<15	Spares shrubs

Adapted from Sombroek *et al.* (1982).

Kenya's ASALs are further characterized by patchy vegetation cover, fragile soils, high temperatures, frequent droughts and wind storms (Eiden *et al.,* 1991). The Gabra rangeland which is the main focus of the current study, is located in northern Kenya and is the most arid of all of the rangelands of east Africa. The Gabra pastoralists rely mainly on camels, sheep and goats to generate income and milk for household consumption (McPeack, 2004).

2.1. Land tenure systems

Three major land tenure systems exist in Kenya, namely, public, communal and private ownership the (Constitution of Kenya, 2010, Chapter V, Article 61); this classification of land tenure system is based on statutory and/or customary law (Lengoiboni *et al.*, 2010). Land tenure provides the legal and normative framework within which all agricultural as well as other economic activities are conducted. Tenure insecurity, whether customary or statutory, therefore, undermines the effectiveness of these activities (Waiganjo *et al.,* 2001). While a substantial portion of land in Kenya is under private ownership, most pastoral lands are owned communally through family lineages or clans, and the land is passed on from one generation to another by inheritance (Nixon, 2009). According to The Constitution of Kenya (2010) Chapter V, Part 1, Article 63, communal land is described as land that is lawfully held, managed or used by a specific community as community forest, grazing areas or shines, or ancestral lands and lands traditionally occupied by hunter-gatherer communities or land lawfully held as trust land by the county governments. Land use actors of pastoral land in Kenya are the pastoralists, who depend on livestock for their livelihood. They move their livestock year round in search of pasture and water rather than bringing fodder to them. The time and pattern of movement is dictated by climate (wet and dry seasons) and availability of pasture, security and watering points, among other physical and biotic factors (Lengoiboni *et al.,* 2010).

2.2. Classification of rangeland vegetation

According to Pratt and Gwynne (1977), rangeland is regarded as land carrying natural or semi-natural vegetation, which provides a habitat for herds of wild or domestic ungulates. Based on this definition, the greater part of East Africa land is classified as rangeland. Spatial distribution of different vegetation types is mainly determined by rainfall and soil properties (Eiden *et al.,* 1991). Spatial heterogeneity of rainfall is also fundamental to the functioning of these ecosystems (Stavi *et al.,* 2008). It should also be distinguished that most of vegetation types of northern Kenya rangelands are also influenced by human activity and wild fauna. Consequently, the present appearance and composition of vegetation is often not giving the original true potential of a site in relation to either vegetation or land use.

Vegetation may be classified based on direct reference to one or more of its visible attributes (e.g., height and form of plants and species composition) or by one or more features of the habitat (e.g., semi desert vegetation). However, it is desirable that vegetation be classified by criteria that can be observed directly so that the result is objective and unequivocal (Pratt and Gwynne, 1977). Two complimentary systems of classification have been recommended regarding rangelands of East Africa by Pratt and Gwynne (1977), namely, ecological and physiognomic classification. The ecological classification indicates land potential criteria that may have to be inferred (indirect observation) in which major combinations of climate, soils and topography are isolated and equated with basic vegetation types. The physiognomic classification indicates present vegetation type based on the criteria that can be observed directly, e.g.,, the form and relative contribution of woody plants *vis-a-vis* grass. However, it should be distinguished that there is relatively little open grasslands in rangelands of northern Kenya but an association of grasses and other range plants growing together. Based on the physiognomic approach, major vegetation types are presented below as indicated by Pratt and Gwynne (1977).

2.2.1. Bushland

Bushland refers to an assemblage of woody plants, mostly of shrubby habit, with a shrub canopy of less than 6 m in height, with occasional emergent and a canopy cover of more than 20%. Sub-types should be classified by reference to the genera of the dominant shrubs like succulent bushland (i.e., bushland dominated by succulent species).

2.2.2. Woodland

Refers to a stand of trees, up to 18 m in height, with an open or continuous but not thickly interlaced canopy, sometimes with shrubs interspersed, and a canopy cover of more than 20%. Grasses and herbs dominate genera of the dominant trees.

2.2.3. Grassland

Grassland is defined as land dominated by grasses and, occasionally, by other herbs, sometimes with widely scattered or grouped trees and shrubs. The canopy cover of trees or shrubs does not exceed 2%. Grassland sub-types should be classified by reference to the height, dominance of annual grasses or other herbs and degree of swampiness if the ecosystem is swampy.

2.2.4. Bushed grassland

Bushed grassland refers to scattered or grouped shrubs, with shrubs always conspicuous but having a canopy cover of less than 20%. Sub-types should be classified by reference to grassland type and genera of the dominant shrubs, indicating (in the order given) grass height, whether the grasses are annuals, dominant genera (grass and shrub) and degree of swampiness incase such vegetation types are found in swampy environments. If the shrubs are acacia, the dominant species should be cited.

2.2.5. Wooded grassland

This refers to grassland with scattered or grouped trees, the trees always conspicuous, but having a canopy cover of less than 20%.

2.2.6. Dwarf shrub grassland

This refers to arid or poor land sparsely covered by grasses and dwarf shrubs not exceeding 1 m in height, sometimes with widely scattered larger shrubs or stunted trees. The prefix 'dwarf' can be applied wherever shrubs are less than 1 m and trees are less than 2 m in height. Dwarf shrub grassland is a form of bushed grassland which has been isolated for individual mention because it is representative of a distinct plant formation of arid regions that occurs in the rangelands of northern Kenya.

2.3. Carbon stocks

Three reserves that regulate the carbon cycles on the earth are documented in the literature; the oceans (39,000 PgC), the atmosphere (750 PgC) and terrestrial systems (2200 PgC) (Batjes, 1996). Although the soil-vegetation carbon pools are small compared with that of oceans, potentially it is much more labile in a short time scale and has attracted more attention because of being more vulnerable to the effects of climate change and disturbance (Hu *et al.,* 1997). Averagely, the soil contains about three times more organic carbon than vegetation (Batjes, 1996; Zhou *et al.*, 2003; Lal 2004; Sheikh *et al.*, 2008; Fynn *et al.*, 2009). Four estimates of SOC mass in the upper 1 m in 1990's included 1220 PgC (Sombroek *et al.,* 1993), 1576 PgC (Eswaran *et al.,* 1993) and 1462-1548 PgC at global scale(Batjes, 1996), of which about 26% is stored in the soil of the tropical regions (Batjes, 1996).

Soil carbon pools comprise of SOC estimated at 1550 Pg C and soil (SIC) at about 750 Pg C both at 1 m depth at a global scale (Lal, 2004b). Estimates of SOCS of Kenya by Batjes (2004) ranged from 1896-2006 Tg in the upper 0-30 cm and 3452-3797 Tg in the upper 0-100 cm as shown in Table 2 whereas Matieu (2010) recorded 1832 Tg for the upper 0-30 cm and 3989 Tg for upper 0-100 cm per km^2 national level. Arid regions (zone VII) have the lowest SOCS of 0-18 t C ha^{-1} than the rest of the country (GEFSOC, 2003; Kamoni *et al.,* 2007). According to Batjes (2004), regional

Table 2. Area weighted concentration of soil organic and inorganic carbon per agro-climatic zones of Kenya

ACZ	Soil organic carbon (kg C m^{-2})			Inorganic carbon (kg C m^{-2})		
	0-30cm	0-50cm	0-100cm	0-30cm	0-50cm	0-100cm
I	7.7-7.9	11.4-11.5	15.4-15.7	<0.1	<0.1	<0.1
II	6.8-6.9	10.0-10.1	13.4-13.7	<0.1	<0.1	<0.1
III	5.2-5.3	7.5-7.6	10.2-10.3	0.1-0.2	0.2-0.3	0.3-0.4
IV	4.6-4.7	6.6-6.7	8.7-8.8	0.2-0.3	0.3-0.4	0.5-0.6
V	3.6-3.7	5.1-5.2	6.8-6.9	0.4-0.5	0.6-0.7	1.1-1.2
VI	2.9-3.0	4.1-4.2	5.7-5.8	0.8-0.9	1.3-1.4	2.5-2.6
VII	2.2-2.3	3.2-3.3	4.4-4.5	1.4-1.5	2.4-2.5	4.3-4.5
All	3.2-3.3	4.6-4.7	6.3-6.4	0.9-1.0	1.5-1.6	2.7-2.8

ACZ; Agro-climatic zones. Source: Batjes (2004).

distribution of SOC and SIC in Kenya varies widely between and within ACZ, with most carbon in the soil attributed to organic matter inputs; however carbonates formation can be significant in some parts of the ASALs due to processes of calcification and formation of secondary carbonates.

2.3. Soil carbon sequestration for mitigating effects of climate change and variability

Carbon sequestration is the process of removing CO_2 from the atmosphere and storing it ‘locking up’ in the soil carbon pool of varying lifetime. The amount of carbon sequestered is the overall balance between photosynthetic gain of CO_2-carbon and losses in ecosystem respiration as well as lateral flows of carbon and predominantly as dissolved and inorganic carbon (FAO, 2009). There is still some uncertainties on the exact size and distribution of grasslands to sequester carbon, e.g., Lal (2004b) observed that total carbon sequestration potential of the world soils vary widely from 0.4Gt carbon to 1.2 Gt carbon per year with rangelands and grasslands contributing 0.01 to 0.3 Gt carbon per year, and dry lands alone having the potential to sequester approximately 1.0 PgC per year if are restored to their ecological potential. Ogel *et al.* (2004) analyzed 45 studies related to management of grasslands and noted that SOC losses of 3 to 5% in temperate and tropical areas, respectively, was associated with degradation of grasslands due to poor management. Conversely, changing management strategies aimed at improving grassland productivity could increase SOC concentration by 14 and 17% in temperate and tropical regions, respectively. This potential of soil to act as a sink of carbon is, however, dependent on antecedent level of SOM, climate, soil profile characteristics and management (Lal, 2004a). Restoration of degraded dry lands could have a major impact on the mitigation of the negative effects of climate change at global scale since the non-forested world’s drylands (excluding hyper-arid regions) is about 43% of the earth’s terrestrial land surface (Batjes, 1999). Soil carbon sequestration may also serve as a bridge in addressing desertification and loss of biodiversity, and co-benefits of carbon sequestration may also provide a direct link to the MDGs through their effect on food and poverty (FAO, 2009).

2.4. Factors influencing SOC pools

Soil organic carbon levels vary in the soil mainly due to climate, topography, vegetation, soil properties and land use change (Sombroek *et al.*, 1993; Batjes, 1996; Amundson, 2001; Rice, 2005; Li *et al.*, 2010). The effects of each factor on the SOC are briefly discussed below.

2.4.1. Climate

Climate is a key factor that regulates SOC levels in the soil; combination of rainfall (soil moisture) and temperature affect plant productivity and microbial activity as well as their decomposition rates (Sombroek *et al.,* 1993; Allen *et al.,* 2010). Enhanced soil moisture concentration increases detritivore abundance and activity, which lead to higher rates of litter decomposition and incorporation of litter into the soil and subsequently, increased SOC concentration and reduced bulk density (Stavi *et al.,* 2008). High temperatures and high soil moisture concentration enhance decomposition rates unless the soils are imperfectly drained and oxygen deficient (Sombroek *et al.,* 1993). Hot climates with restricted water have the lowest levels of SOC because plant production is limited (Rice, 2005). Variations in temperature across drylands make considerable difference in water use efficiency, resulting in a strong impact on biomass production, the length of growing season and SOC levels. The length of growing season controls the amount and kind of biomass that is produced, and has significant impact on the concentration of SOC in the soil (Lal, 2004a). Generally, SOCS on a global scale increases with precipitation and decreases with temperature (Hiederer, 2009). Impacts of projected climate change on soil carbon has been studied for some regions, e.g., an increase in temperature would deplete the SOC in the upper layers of soil by 28% in humid zones, 20% in sub-humid zones and 15% in the arid zones (Bottner *et al.*, 1995).

2.4.2. Vegetation

The amount of SOC in the soil depends on the supply of organic matter *in situ* in terms of biomass production and their decomposition rates (Sombroek *et al.*, 1993; Rice, 2005). According to Rice (2005), grasses tend to promote higher SOC because they not only have high productivity but also allocate more photosynthate below-ground. The high density of grass roots tend to favour formation of SOC, while in forested areas, a greater proportion of carbon sequestered is in woody biomass. The quantity of organic carbon in the soil is, therefore, a function of the amount of plant material entering the soil, the decomposition rate of those residues and the soil chemistry and mineralogy. Allen *et al.* (2010) further observed that at the plant level/ pedon scale, the contributors of spatial variability of SOC are vegetative patterns and plant community dynamics, the size and morphology (e.g., trees, shrubs and grass). Spatial distribution of plants affects the areas where carbon is input into the soil and also the location of other sources of SOC like the soil microbial biomass and soil fauna.

2.4.3. Soil properties

Soil properties, like soil texture, pH, soil moisture concentration and mineralogy influence the level of SOC content, e.g., the amount of clay concentration affects the capacity to have stable soil aggregates, favoring the protection and stabilization of SOC (Rice, 2005). The effect of clay concentration in the soil is a more dominant factor in deeper soil layers than in upper layers where climate plays a major important role in determining the amount of SOC levels (Hinderer, 2009).

2.4.4. Topography

The effect of topographical factors on SOC has been studied and reported in the literature. Li *et al.* (2010) observed a strong relationship between topographical factors of aspect and slope, and SOC in cold temperate mountainous forests. Prichard *et al.* (2000) noted that ecosystem processes and associated carbon storage differed between high and low elevations in Olympic Mountains of the USA. The ecosystem processes include local disturbance regimes, decomposition rates and ecosystems productivity. According to Thompson and Kolka (2005), SOC concentration increased with increased elevation in forested watershed, e.g., 71% of SOC variability in the region was explained by three to five topographic or terrain attributes calculated directly from a 300-m DEM.

2.4.5. Land use change

Since industrial revolution, land use change and soil cultivation has contributed to global emission of carbon estimated at 136±55 Pg C; this includes those from deforestation, biomass burning, conversion of natural to agricultural ecosystems, drainage of wetlands and soil cultivation (Lal, 2004a). For instance, Solomon and Lehmann (2000) reported that clearing and cultivation of native tropical woodlands in Tanzania resulted in a reduction of about 56% carbon in the A horizon of chromic luvisols. In grasslands and savannah ecosystems, SOC variations depend on grazing intensity and fire return intervals (Ardö and Olsson, 2002). Expanding croplands to meet the needs of the growing human population, changing diets and biofuel production comes with a cost of reducing carbon stocks in natural vegetation and soils; soil carbon is released when bare soil exposes organic matter to oxidation and erosion (West *et al.*, 2010). Generally, land use change globally contributes 0.3 to 3 PgC year^{-1} or approximately 21% of the total fossil fuel emission (Houghton, 2007). However, the adoption of restorative land use and conservation tillage with cover crops like crop residue mulch, the use of compost and manure, and other forms of sustainability management of soil and water resources is necessary, can potentially prevent or mitigate the effects of climate change (Lal, 2004b).

2.5. Characteristics of SOC

Soil organic carbon is heterogeneous in nature and is composed of several pools that can be grouped broadly into three depending on their turnover rates; active or labile carbon pool, slow pool and the resistant or passive pool (Rice 2005; Allen *et al.*, 2010). Table 3 summarizes the three groups of soil carbon pools, soil carbon fraction (%) and turnover period. Labile carbon pool (carbohydrates and microbial biomass) have attracted much attention because they are more vulnerable to climate change and disturbance, and play a vital role in both carbon and nutrient cycling (Hu *et al.*, 1997; Gulde *et al.*, 2008), and is also characterized by rapid turnover rates (Rühlmann, 1999; Gulde *et al.*, 2008). Meanwhile, the slow pool consists of humus and clay-complexed carbon soil fraction while resistant carbon (passive) consists of charcoal carbon, phytoliths and carbonates soil fractions (Allen *et al.*, 2010). Three possible factors that have been suggested for slow turnover rates of the slow pool are; the chemical nature of SOC, (e.g., with increasing aromaticity, it leads to an increase in spatial inaccessibility to micro-organisms and extracelluar enzymes due to micro-aggregation),

Table 3. Soil carbon pools, their percentage and turnover period

Soil C pool	Pool C/ total C (%)	Turnover period in years
Labile (active) C	0.5-5	<10
Slow C	30-50	10-200
Resistant (passive) C	1-30	>100

C – carbon. Adopted from: Allen *et al.* (2010).

physical separation of soil particles and sorption of carbon on mineral surface and/ or interaction with mineral particles (Allen *et al.,* 2010).

2.6. Methods of estimating SOCS

Soil carbon stocks can be estimated either by measuring soil carbon directly from a soil sample on site or laboratory or indirectly through the relationships between other predictor variables and soil carbon concentration (Fynn *et al.,* 2009). Direct methods are very accurate but labour intensive, costly, time consuming and only provides site specific information (Salahuddin, 2006), making replication in time and space limited due to the labour required for soil core acquisition, processing and analysis (Throop and Archer, 2008). Sampling cost can be reduced by stratification of the area under study into strata that are homogenous for characteristics that are being measured. These are the characteristics that affect SOCS and fluxes of carbon (Fynn *et al.,* 2009).

Organic carbon is universally determined by oxidation into carbon monoxide, and is directly measured as CO_2 or by weighing loss of the sample or by back-titration of excess of the oxidant added (Batjes, 1996). Both dry and combustion methods give results of carbon values that are comparable because they all recover 100% of the organic carbon. However, the Walkey-Black method gives variable recovery of soil carbon. Nonetheless, standard conversion factors of 1.33 for incomplete oxidation and a factor of 58% for the soil carbon to organic matter ratio are commonly used to convert Walkey-Black carbon to total organic carbon content, even though the true conversion factors vary greatly between and within soils because of difference in the nature of organic matter with soil depth and vegetation type (Batjes, 1996).

Indirect methods are non-intrusive, are relatively of low cost and can provide spatially continuous information over target areas on a repetitive basis (Salahuddin, 2006). Fynn *et al.* (2009) grouped indirect methods into two, namely: models to estimate carbon stocks given the sequence of values of factors that affect carbon stocks (climate, vegetation types and grazing regimes), and statistical relationships "calibrated" with previously obtained data, where the relationship and/ or equations uses values of variables that are cheap and easy to measure to estimate carbon stocks. Input variables can be quantitative, like the amount of radiation reflected by soils and vegetation in each of several spectral bands, or qualitative, like soil series.

Remote sensing technology, as one of the indirect methods has been recently used to estimate above-ground carbon stocks and changes in carbon stocks (e.g., Anser *et al.,* 2003; Throop *et al.,* 2008; Sanchez-azofeifa *et al.,* 2009; Matieu, 2010). Despite this progress, there still exist some limitations. Sanchez-azofeifa *et al.* (2009) documented three limitations when using remote sensing data to estimate above-ground carbon and its changes in forested areas. It includes the definition of methods and algorithms to accurately estimate forest age, provision of techniques that yield accurate estimates of deforestation rates in both tropical dry and wet forest environments, and the strong need to develop a new approach to link biophysical variables (e.g., leaf area index) to spectral reflectance to support spatially distributed carbon sequestration models.

Remote sensing of soil carbon is based on the existence of a relationship between spectral reflectance and carbon concentration in air-dried soil of the upper horizon in the laboratory (Propastin and Kappas, 2010). Because the current satellite sensors do not penetrate beyond the soil surface, it limits the use of satellite imagery and remote sensing in measuring soil carbon pools and its dynamics (Johnson *et al.,* 2004). However, vegetation indices like the as NDVI and SAVI derived from satellite data has been used to identify and classify vegetation types (Boettinger *et al.*, 2008). Linking above-ground vegetation cover to SOC pools would provide important information on plant type (vegetation type) impacts on carbon sequestration in soils (Throop *et al.*, 2008). Matieu (2010) documented some literature on the successes of using remote sensing to track forest area and cover change, and further described major characteristics of imaging remote sensing instruments operating in the visible and infrared region described in terms of spatial, radiometric, spectral and temporal resolutions, these sensors can also be used in rangelands to assess carbon stocks. The spatial resolution refers to the size of the smallest possible feature that can be detected by the remote sensor; resulting to three types of spatial resolutions; coarse, mid and high resolutions. Table 4 above illustrates different sensors that are available for monitoring forest cover change. Temporal resolution of remote

Table 4. Main sensors of different spatial resolutions for monitoring forest cover change

Sensor resolution	Example of the sensor	Minimum mapping unit (ha)
Coarse (250-1000 m)	SPOT-VGT (1998- now), Terra-MODIS, Envisat-MERIS (2004-now) AVHRR	~100 ha, ~10-20
Medium (10-60 m)	Landsat TM or ETM+, SPOT HM, Terra-Aster, AWiFs LISS II, CBERS HRCCD, DMC ALOS PALSAR, ERS1/2 SAR, JERS-1, ENVISAT-ASAR RADARSAT 1	0.5-5
High (<5 m)	SPOT HRV, IKONOS, Quickbird, Aerial photos	< 0.1

Adopted from: Matieu (2010).

sensing system relates to the frequency with which images of a given geographical location can be captured repeatedly at a given time period (Matieu, 2010).

2.7. Soil bulk density

Soil bulk density, expressed as mass per unit volume of soil (Allen *et al.*, 2010), is very critical in calculating SOCS. It is used to convert SOC concentration percentage by weight to concentration by volume (Batjes, 1996; Allen *et al.*, 2010) although it varies depending on structural conditions of the soil, specifically, the mineralogy, water concentration and compaction (Batjes, 1996). Other factors affecting soil bulk density include, cropping (through tillage and residue management), grazing (grazing intensity and pasture type), vegetation and climate (Allen *et al.*, 2010). Soil bulk density is usually measured directly by determining the soil mass and volume or indirectly by the attenuation or scattering of radiation. The choice of method, therefore, depends on the purpose of measurement, time available, required accuracy and precision, repeated measurement at the same location, cost, operator expertise and equipment availability (Cresswell and Hamilton, 2002). Core sampling or field excavation with water replacement methods is most preferred when using direct measurement to determine soil bulk density. Although core sampling method is widely, used it is susceptible to some errors when sampling soil cores in dry or stoney soils where it is difficult to obtain a good core (Batjes 1996; Cresswell and Hamilton, 2002).

CHAPTER THREE

MATERIALS AND METHODS

3. Description of the study area

3.1. Geographical location of the site and climate

The study was conducted in the grazing unit (‘*rage’*) of Gabra rangeland of Kalacha location in Chalbi district (Marsabit County) in northern Kenya as shown in Figure 1. The area lies between latitude 3°14'12.10" N and 3°11'08.37" N, and between longitude 37°17'21.92 E and 37°22'16.36". Most of the area is classified as zone VI, with a climate that is characterized by high solar radiation input through the clear skies, high radiative heat losses at night, low precipitation, high moisture losses and prolonged water deficits (Sombroek *et al.,* 1982). It receives an annual rainfall of 157 mm (Olukoye *et al.,* 2003), which is determined by the movement of the inter- tropical convergence zone (ITCZ) and the prevailing conditions of trade winds that fall within east Africa (Eiden *et al.,* 1991). Rainfall displays both temporal and spatial variation, and is bimodal in distribution, while drought is a common phenomenon in the region and puts servere stress on the already fragile arid and semi - arid ecosystem (Eiden *et al.,* 1991).

3.2. Vegetation

The study site had low vegetation cover, with the acacia species, shrubs and forbs being major vegetation cover types. The dominant tree species in the grazing unit was *Acacia tortilis.* Other species found were *Acacia nubica, Acacia seyal, Balanite spp,* colonies of *Hyphaena coriacea* (doum palms) and *Salvadora persica* At the time of the study, larger areas were completely bare and covered with desert pavement, with complete absence of grass growth.

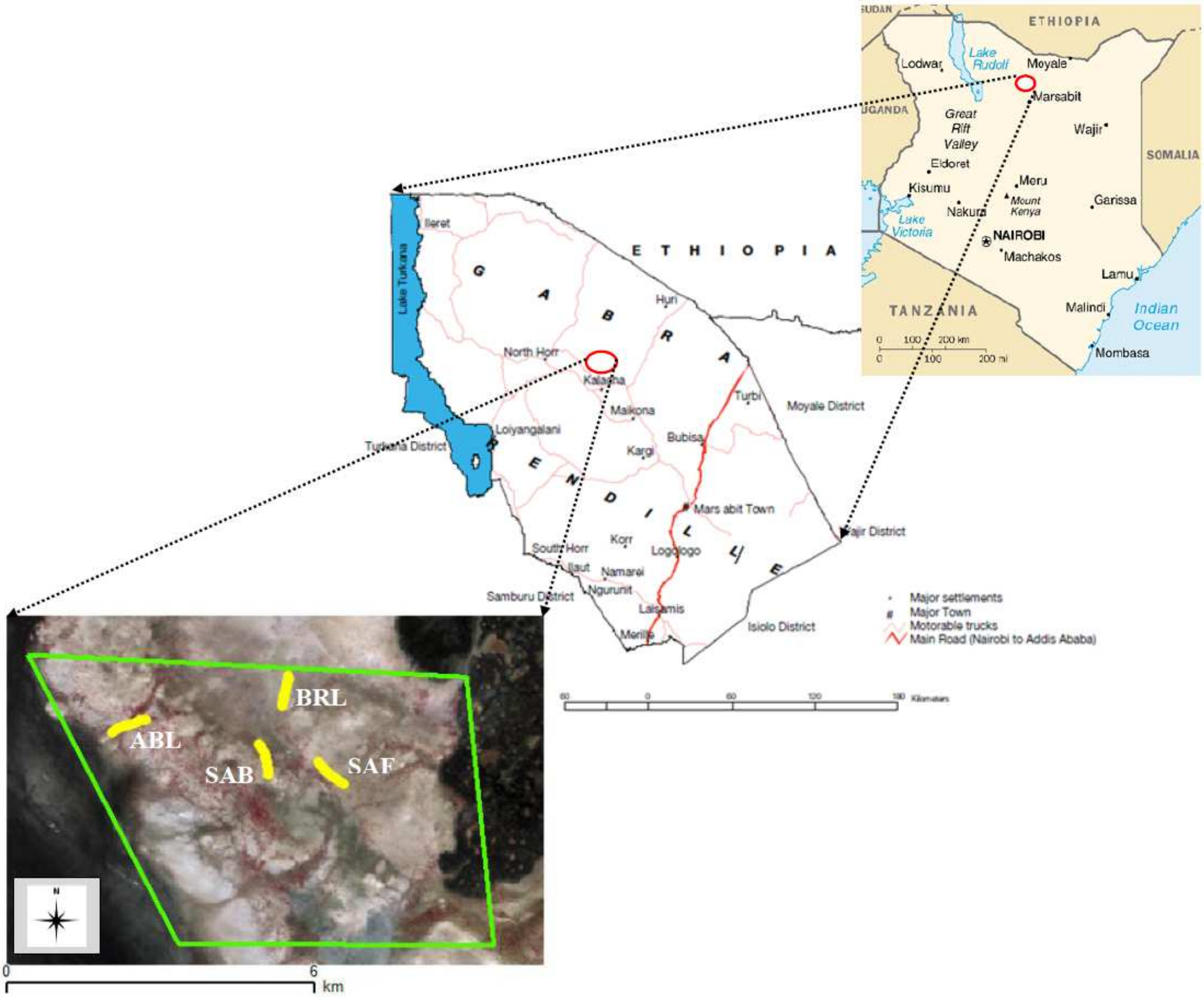

Figure 1. Map of the study area: BRL: bare land. SAB: sparsely distributed acacia with bare ground cover, SAF: sparsely distributed acacia with forb undergrowth and ABL: acacia bushland cover

3.3. Soils

Soils of the study site are sandy loam in texture, saline, sodic and calcareous, shallow to moderate deep and pale brown, with the parent material being sand mixed with some volcanic ashes.

According to the FAO-UNESCO systems of classification, the soils are classified as Cambic Arenosols (Aridosols or Solonchaks). The high salt concentration causes surface sealing and reduces water infiltration (Olukoye *et al.*, 2003). According to Muya *et al.* (2011), soil structural degradation has taken place at different rates through pulverization in the mountainous and hilly areas, compaction in foot slopes and dispersion in low lying areas. The soils are acidic in nature (pH <6.5), implying a possibility of aluminum and other heavy metal toxicity. Major limiting soil factors in the area are; low organic matter content, high salinity and extremely high exchangeable sodium percentage (Muya *et al.*, 2011).

3.4. Classification of vegetation cover types

Landsat 5 Thematic Mapper (TM) satellite image with a resolution of 30 x 30 m was used to classify vegetation into four different cover types based on image interpretation. The image was first obtained online from http://www.glovis usgs.gov on 10th January, 2011 and processed with ERDAS IMAGINE 9.1 software followed by identification of different vegetation cover types, resulting into four different covers as shown in Plates 1, 2, 3 and 4. The four identified vegetation cover types also formed the basis of stratifying the grazing unit into four strata. The geographical positions of the centers of each of the four vegetation cover types were identified, marked, recorded and loaded into Trimble Goex GPS system. Subsequently, ground-truthing to locate each vegetation cover type in the field was done with the help of a GPS, Marsabit district physical map and experienced herders selected from the site. The four vegetation cover types identified were acacia bushland cover (ABL), sparsely distributed acacia with forb undergrowth (SAF) and sparsely distributed acacia with bare ground cover (SAB).

Plate 1. Acacia bushland cover

Plate 2. Sparsely distributed acacia with forb cover

Plate 3. Sparsely distributed acacia with bare ground cover

Plate 4. Bare land

3.5. Soil sampling for determination of SOC concentrations

A transect line of 750 m in length was laid across each vegetation type and sampling of soils done at intervals of 50 m along the transect line, giving a total of 15 replicates per each cover type and a total of 60 samples. Soil samples were collected to a depth of 0-15 cm in an area of 1 m^2 in a Z pattern using a soil auger along the transect line. Four sub-samples of soil were collected at every corner of the 1 m^2 mixed in a larger plastic bucket, and 500 g sample was pooled into a small paper bag and labeled to indicate vegetation cover type and sample ID number. The geographical position of every sampling point was taken using a GPS (Trimble GeoXT) and recorded.

Plate 5. Soil sampling in *'rage'* grazing unit

3.6. Soil sampling for determination of bulk density

Soil for determination of bulk density was sampled along the transect line of 750 m at an interval of 50 m on each vegetation cover type. Coring rings of known volume (100 cm^3) were used to collect the samples as shown in Plate 6. Sampling was done carefully by driving the coring ring into the soil using a hand sledge and a block of wood so as not to disturb the soil. The coring ring containing the soil was then lifted with care to prevent any loss of soil from the ring. Excess soil was trimmed with a sharp knife so that the soil was exactly flashing with the ends of the coring rings, after which the coring rings were then closed on both sides with plastic caps and labeled with strata name, and soil sample ID number. The same procedure was applied for all the 60 samples collected from the four vegetation cover types. Similarly, the geographical position of every sampling point was taken using a GPS (Trimble GeoXT) and recorded.

Plate 6. Coring ring with soil sample for soil bulk density determination

3.7. Laboratory analyses

3.7.1. Determination of total SOC

Analysis of the total SOC concentration was performed at NARL in Nairobi, which is under the management of KARI using the colourimetric method. This method is a wet-oxidation procedure that uses potassium dichromate with external heat as described by Anderson and Ingram (1993). 'Wet' oxidation by acidified dichromate of organic carbon follows the reaction as shown in equation 1 below:

$$2Cr_2O_7^{2-} + 3C + 16H^+ \rightarrow 4Cr^{3+} + 3CO_2 + 8H_2O \qquad \text{(Equation 1)}$$

For complete oxidation of all SOC in the soil samples, the reagents are heated at 150^{o}C for 30 minutes. The colourimetric method determines the amount of SOC in the samples by the amount of chromic ions (Cr^{3+}) produced in the above reactions depicted in equation 1.

3.7.2. Laboratory procedures for determination of total SOC

Soil samples were first dried at room temperature before passing them through a 2 mm sieve. The coarse fraction (particles >2 mm) was weighed to determine the percentage of the coarse fraction. One gram of the soil sample (from <2 mm) was scooped, grounded and passed through a 0.05 mm screen into a labeled digestion tube. The standard samples and reagent blanks were also included in each step of analysis. 2 ml of deionized water was then added to each soil sample using a pipette (deionized water was not added to the standards since it was already added during preparation stage), 10 ml of 5% potassium dichromate solution was also added into both the standards and sample tubes, and ($K_2Cr_2O_7$) allowed to completely wet the sample. Slowly, 5 ml of concentrated H_2SO_4 technical grade was added from a bottle-top dispenser in drops of 1 ml of the acid at a time while swirling on a vortex mixture to avoid violent reaction and then the digest was heated at 150° C for 30 minutes. The samples were then removed from the heater and allowed to cool, 50 ml of 0.4% Barium Chloride solution was then added and allowed to stand overnight to ensure complete mixing. Carbon concentration was then read on the spectrophotometer at 600 nm. No calibration curves were drawn since the spectrophotometer was computerized and gave the results automatically after it was calibrated with two standards of 0 and 12.5 mg C/ml as lowest, and the highest values, respectively.

3.7.3. Soil bulk density

Analysis of soil bulk density was also performed at the NARL following the methodology described by Cresswell and Hamilton (2002). Oven-proof container was first weighed before carefully pushing out the trimmed soil cores into it. The oven-proof container and the soil were again weighted and the weight recorded. The same procedure was repeated for all the sixty soil core samples before oven drying it in a well ventilated oven at 105° C for 48 hours until the weights of the soil were constant. The container with the soils was removed from the oven and cooled in the desiccator before weighing the container and the oven dried soil. Soil bulk density (g cm^{-3}) was then calculated as shown in equation 2 below:

$$BD_{Sample} = ODW_{Sample} / CV_{Sample} \qquad \text{(Equation 2)}$$

where BD_{Sample} is the bulk density (g cm^{-3}) of the soil sample, ODW_{Sample} the mass (g) of oven dried soil core and CV_{Sample} the core volume (cm^3) of the soil sample.

3.7.4. Calculation of SOCS

The SOCS (t C ha^{-1}) were calculated from the SOC concentration (%) obtained from laboratory analyses as indicated in equation 3 below:

$$C\ (t\ ha^{-1}) = C\ (\%) * \rho * D \qquad \text{(Equation 3)}$$

where $C\ (t\ ha^{-1})$ is the SOCS (t ha^{-1}), $C\ (\%)$ the concentration of SOC (%), ρ the soil bulk density (g cm^{-3}) and D the depth of sampling in cm (0-15 cm).

3.8. Computation of Vegetation Indices

To estimate SOCS indirectly from vegetation indices, Normalized Difference Vegetation Index (NDV) and Soil Adjusted Vegetation Index (SAVI) were computed from Landsat TM 5 reflectance image using ERDAS IMAGINE 9.1 software. Normalized difference vegetation index for each pixel was derived according to the relationship described by Rouse *et al.* (1973) as shown in equation 4 below:

$$\mathrm{NDVI} = \mathrm{NIR} - \mathrm{R} / \mathrm{NIR} + \mathrm{R} \qquad \text{(Equation 4)}$$

where NIR and R are reflectance in Near Infra–Red and Red bands, respectively.

Soil Adjusted Vegetation Index was computed using the formula of Huete (1988) as indicated in equation 5 below:

$$\mathrm{SAVI} = (1 + n)\,(\mathrm{NIR} - \mathrm{R}) / \mathrm{NIR} + \mathrm{R} + n \qquad \text{(Equation 5)}$$

where $n = 0.5$. The SAVI adjusted factor, n, is used to compensate for the influence of varying soil backgrounds on the measured plant index, and is typically assigned a value of $n = 0.5$ (Huete, 1988).

3.9. Statistical analyses

Statistical analyses of each of the measured variable were performed with GLM (general procedures model) procedure of SAS version 9.0 software (SAS Institute Inc., 2010). Homogeneity of variance and normality of distribution of all dependent data were verified graphically prior to analyses. Statistically significant interactions were subjected further to one way ANOVA with a SLICE command of PROC GLM. Multiple comparisons of means of SOC concentration, soil bulk densities and SOCS for the four vegetation cover types was done by Tuskey’s HSD ($p<0.05$). The relationship between vegetation indices (NDVI and SAVI) and SOCS was derived from simple linear regression. Graphic presentation was done with Sigma plot (Version 12.0).

CHAPTER FOUR

RESULTS AND DISCUSSION

This Chapter presents the results and discussion of the laboratory analyses of soil samples for SOC concentration, bulk density and SOCS computed from the two mentioned measured soil parameters (SOC concentrations and soil bulk density) collected under the four vegetation cover types at a depth of 0-15 cm in the *'rage'* grazing unit of Gabra land, Kalacha location in northern Kenya. The results presented consist of three sub-sections; relationships between (i) vegetation cover type and SOC concentrations, (ii) vegetation cover types and bulk density, (iii) vegetation cover types and SOCS and (iv) the relationship between SOCS and vegetation indices of the identified vegetation cover types (NDVI and SAVI).

4.1. Soil organic carbon

The means of SOC concentrations (%) for each vegetation cover type observed during field survey at a depth of 0-15cm are presented in Figure 2 (ABL, 0.59±0.14; BRL, 0.18±0.05; SAF, 0.47±0.04; SAB, 0.28±0.07). The overall mean of SOC concentration for the four vegetation cover types was 0.38±0.18%, with a coefficient of variation (CV) of 21.26 ($r^2 = 0.86$, $P<0.05$). The SOC concentrations were different under the four vegetation cover types ($P<0.05$), a finding which concurs with that of Yimer *et al.* (2006). As expected, the SOC concentration under BRL was lower than that of the other vegetation cover types and higher in ABL, supporting the idea that litter drop is one of the most important ways of carbon inputs into soil. Stavi *et al.* (2008) observed similar relationships, while Bird *et al.* (2002) noted that organic inputs by plants occur via litter drop, root

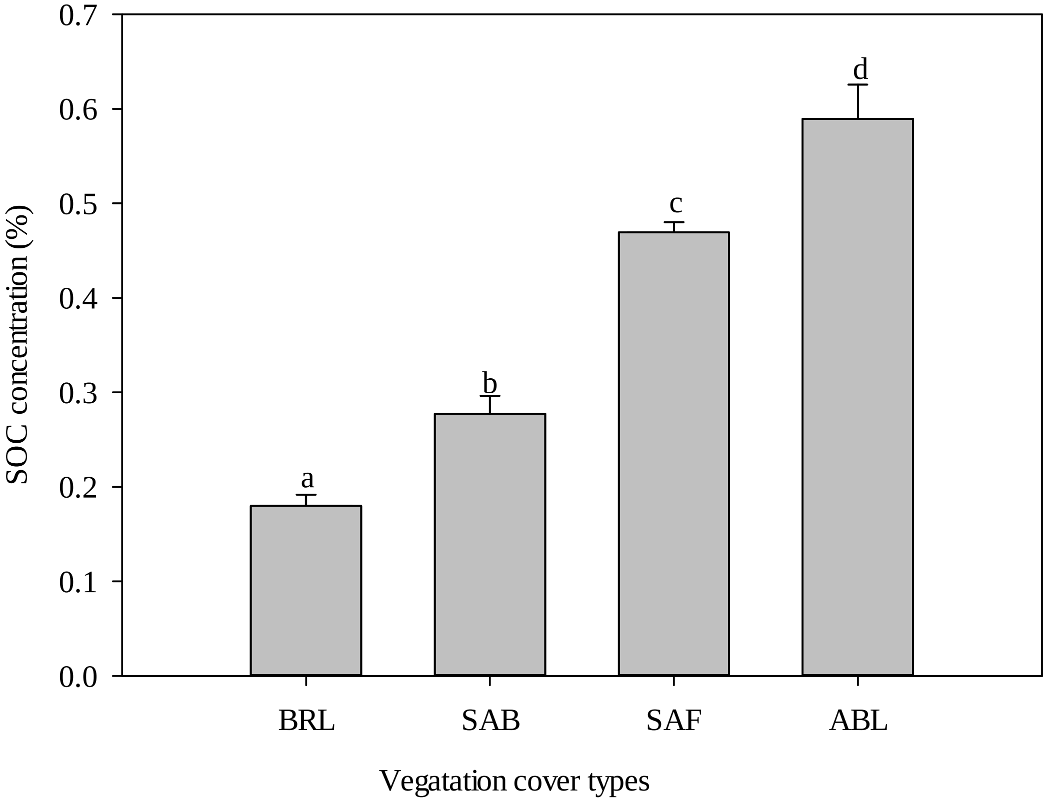

Figure 2. Means of SOC concentration (%) at a depth of 0-15 cm for each vegetation cover type; the bars represent standard errors of the mean. $^{a, b, c, d}$ are different ($P<0.05$). BRL: bare land. SAB: sparsely distributed acacia with bare ground cover, SAF: sparsely distributed acacia with forb undergrowth and ABL: acacia bushland cover

exudates and root mortality. Microclimate under ABL can be characterized by less direct radiation, smaller temperature amplitude and low evaporation rates, which explains the possibility of high soil moisture concentration under ABL relative to BRL though it was not measured. Soil moisture increases the rate of litter decomposition and organic carbon incorporated into the soil and, therefore, SOC decreases with reduction in vegetation cover. Growth pattern of plants also affects the location of other sources of SOC like soil microbial biomass and soil fauna, these components tend to accumulate around areas with already high SOC concentration, and further contribute to higher SOC concentration in areas under vegetation cover compared to bare land (Allen *et al.*, 2010). Roots of acacia trees and shrubs influence soil aggregates directly via root carbon inputs, which promote aggregate formation directly and/ or indirectly by exerting pressure that both consolidates and fragments soils (Bird *et al.*, 2002). Soils with good aggregates form favourable habitat for soil microorganisms, which leads to higher microbial activity that accelerates the rate of litter decomposition.

The overall mean values of SOC concentration of 0.38 % found in the current study is closely similar to those reported by Lal (2001) for dry soils (SOC concentration of 0.5 %). This is below the critical limit of 2-4% documented in the literature as an indicator of soil quality (Muya *et al.,* 2011). These low values of SOC concentration is attributed to land degradation by overgrazing, decreasing soil fertility, loss of bio-diversity (Batjes, 2004), soil type (Arenosols) and climatic factors (Sombroek *et al.*, 1993). It may also be ascribed to high soil acidity, high compaction and high sodicity/ salinity (Muya *et al.,* 2011). Salt affected soils are subjected to increased losses due to dispersion, erosion and leaching, resulting to lower SOC contents (Wong *et al.,* 2010). Infertile soils like Arenosols, Planosols, Regosols and Solonetz predominate in the ASALs, and normally contain very little SOC (Batjes, 2004).

Even with no vegetation cover in BRL, still low levels of SOC (0.18±0.05 %) were recorded. This may be linked to the existence of previous vegetation that may have contributed to SOC pools with slow turnover rates before the soil surface became bare. It could also be due to deposition of litter from vegetated areas within the range unit by wind and/ or animal movements.

4.2. Soil bulk density

The separate means of soil bulk densities (in g cm $^{-3}$) for each of the four different vegetation cover types at a depth of 0-15 cm identified in the field are given in Figure 3 (ABL, 1.15±0.10; BRL, 1.32±0.08; SAF, 1.14±0.10; SAB, 1.23±0.14). The overall mean was 1.23±0.14 g cm^{-3}, with a CV of 9.04 (r^2 =0.52, $P<0.05$). Soil bulk densities under BRL and SAB were similar but different from that of ABL and SAF that were alike ($P<0.05$), with BLR and SAB having higher mean values compared to those of SAF and ABL, and ABL being the least. The overall mean value of bulk density recorded (1.23 g cm^{-3}) is comparable to other observations in Kenya (Verdoodt *et al.,* 2009; Muya *et al.,* 2011). The current results also agree with the findings of Kahi *et al*. (2009) who reported soil bulk densities of 1.18 g cm^{-3} for soils under *A. tortilis* vegetation cover and 1.23 g cm^{-3} for soils under bare land areas in Baringo rangelands of Kenya. The higher values of soil bulk densities under BRL and SAB relative to those of ABL and SAF were expected given that the incorporation of organic carbon was lower as also reported by Pande and Yamamoto (2006). Loss of vegetative and litter cover coupled with rangeland degradation allows direct impact of rain drops on bare soils, resulting to enhanced splash impacts, mechanical crust formation, surface sealing (Stavi *et al.,* 2008), and may also produce hydrophobic substances that can reduce water infiltration into soil (Snyman and du Preez, 2005). The lower soil bulk density values under ABL and SAF may also be attributed to improved soil microporosity due to improved microclimate, higher SOC concentration input and improved soil aggregate relative to BRL and SAB.

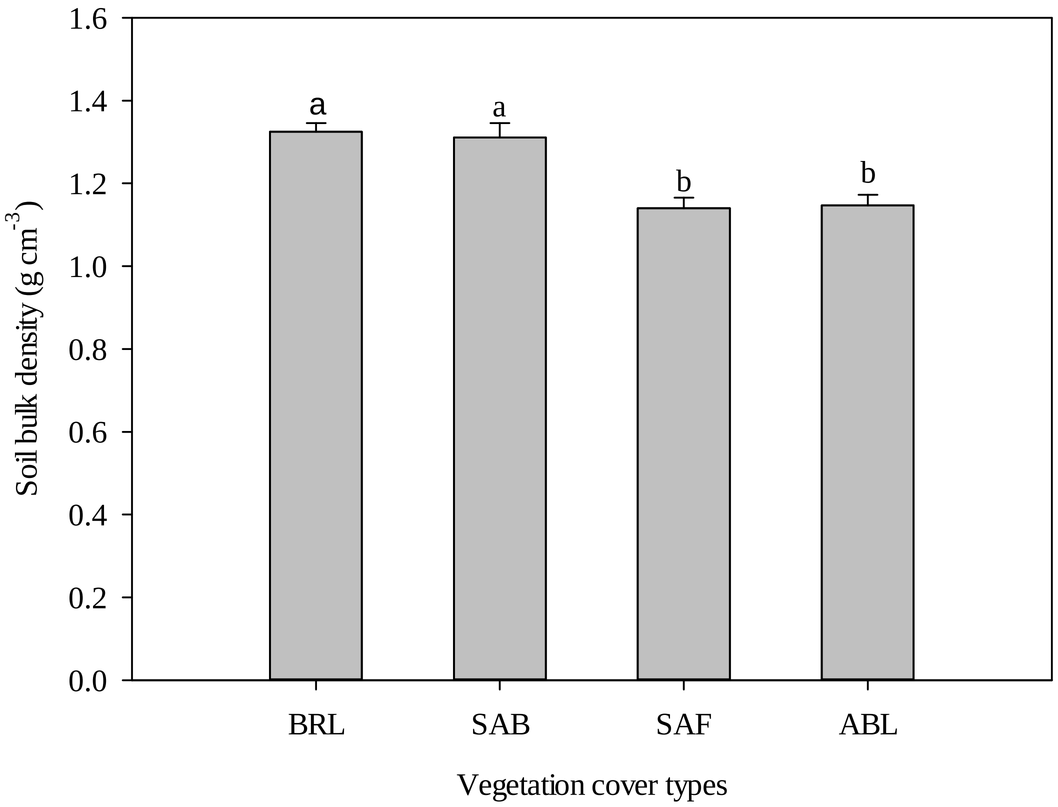

Figure 3. Means of soil bulk densities in g cm $^{-3}$ at a depth of 0-15 cm for each vegetation cover type, the bars represent standard errors of the mean. $^{a, b,}$ are different (P<0.05). BRL: bare land SAB: sparsely distributed acacia with bare ground cover, SAF: sparsely distributed acacia with forb undergrowth cover and ABL: acacia bushland cover

4.3. Soil organic carbon stocks

Figure 4 shows least squares means (t C ha^{-1}) of SOCS under the four different vegetation cover types at a depth of 0-15 cm (ABL, 10.05±2.02; BRL, 3.53±0.79; SAF, 8.23±0.97; SAB, 5.42±1.51). The overall mean of SOCS was 6.76±2.85 ($r^2 = 0.85$, $P < 0.05$) with a CV of 19.44. The SOCS

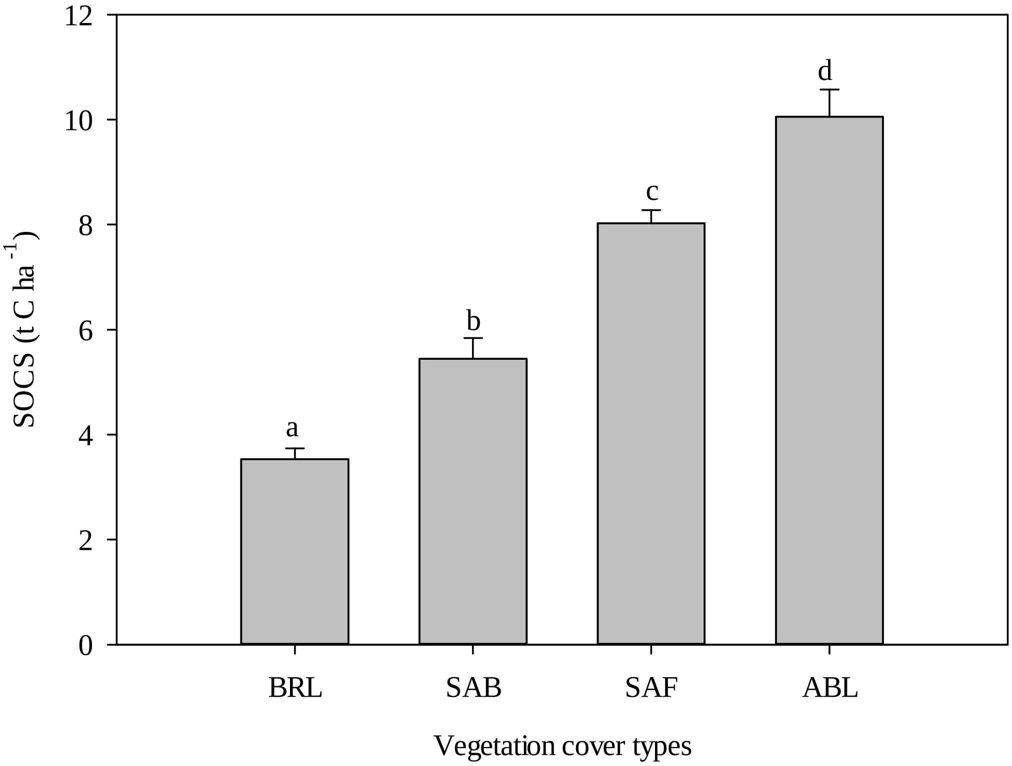

Figure 4. Mean of SOCS in t C ha $^{-1}$ at a depth of 0-15 cm for each vegetation cover type; the bars represent standard errors of the mean. $^{a, b, c, d}$ are different (P<0.05). BRL: bare land. SAB: sparsely distributed acacia with bare ground cover, SAF: sparsely distributed acacia with forb undergrowth and ABL: acacia bushland cover

differed among the four vegetation cover types ($P<0.05$), with a lower and higher mean value for BRL and ABL, respectively. The SAF and SAB had intermediate mean values of SOCS, a finding consistent with those of Yimer *et al.* (2006) and Li *et al.* (2010).

The differences in SOCS is highly associated with vegetation cover type; this suggests that there is a fundamental difference in net primary productivity and carbon cycling processes within each vegetation cover type. Higher SOCS recorded under ABL can be linked to higher litter production, which is incorporated into the soil from *Acacia tortilis* (dominant plant species) compared to other vegetation cover types. It may also be ascribed to reduced solar radiation input into the soil due to protection from the canopy cover, leading to relatively higher soil moisture concentration, which promotes higher root decomposition under ABL. The least mean values observed for BRL could be attributed to; loss of root carbon, leading to a reduction in carbon inputs from the roots and leaf litter, reduced microbial activity due to increased soil temperature relative to ABL and SAF (Mills and Fey, 2004), and loss of top soil through erosion and increased soil compaction, resulting to increased soil bulk density (Mills and Cowling, 2010). Soil compaction reduces water infiltration and increases run - off during rainy seasons under BRL, causing a decrease in the water available for plant growth. Additionally, less pore space can limit gas exchange and reduce root growth; both mechanisms suggest that soil compaction reduce plant production and SOCS (Pineiro *et al.*, 2010).

The overall mean of SOCS recorded (6.76 t C ha^{-1}) in the current study was comparable to those reported earlier (0-18 t C ha^{-1})in a depth of 1m by GEFSOC (2003) for hot arid land (Zone VII) of northern Kenya, and 7.5- 9.9 t C ha^{-1} for degraded rangelands of west Africa (Batjes, 1999), but less compared to those found in humid to semi-humid zones of 18-30 t C ha^{-1} (GEFSOC, 2003; Kamoni *et al.,* 2007). Lower SOCS observed can be attributed to soil structural degradation that has taken place through pulverization, compactions, soil particle dispersion, low organic matter inputs, high pH, high salinity and extremely high exchangeable sodium percentage (Muya *et al.,* 2011).

Overgrazing in the rangeland under low but highly variable precipitation, both in space and time, and high solar radiation inputs, may also account for the lower SOCS levels compared to those of humid zones (Fynn *et al.*, 2009). Overgrazing destroys the most palatable and useful species in the plant mixture and reduces the density of plant cover, leading to an increase in erosion hazards that deplete SOC pools (FAO, 2005).

4.4. Relationship between SOCS and vegetation indices (NDVI and SAVI)

Figure 5 shows the relationship between the average means of SOCS (t C ha^{-1}) and the average means of normalized difference vegetation index (NDVI) of four vegetation cover types. The model was evaluated using the goodness of fit creteria determined by R^2 , where the highest R^2 values inidicate best fit of the model to the data. The SOCS had a high positive correlation with NDVI (R^2=0.89), indicating that as NDVI increases, SOCS will also increase. A similar trend was observed on the relationship between the average means of SOCS and the average means of SAVI (R^2 = 0.89) as shown in Figure 6. Nisha Wani and Dadhwal (2010) observed similar relationships between NDVI values derived from remote sensing data and soil carbon densities. This clearly demonstrate that NDVI and SAVI can be used to estimate spatial variability of SOCS in arid and

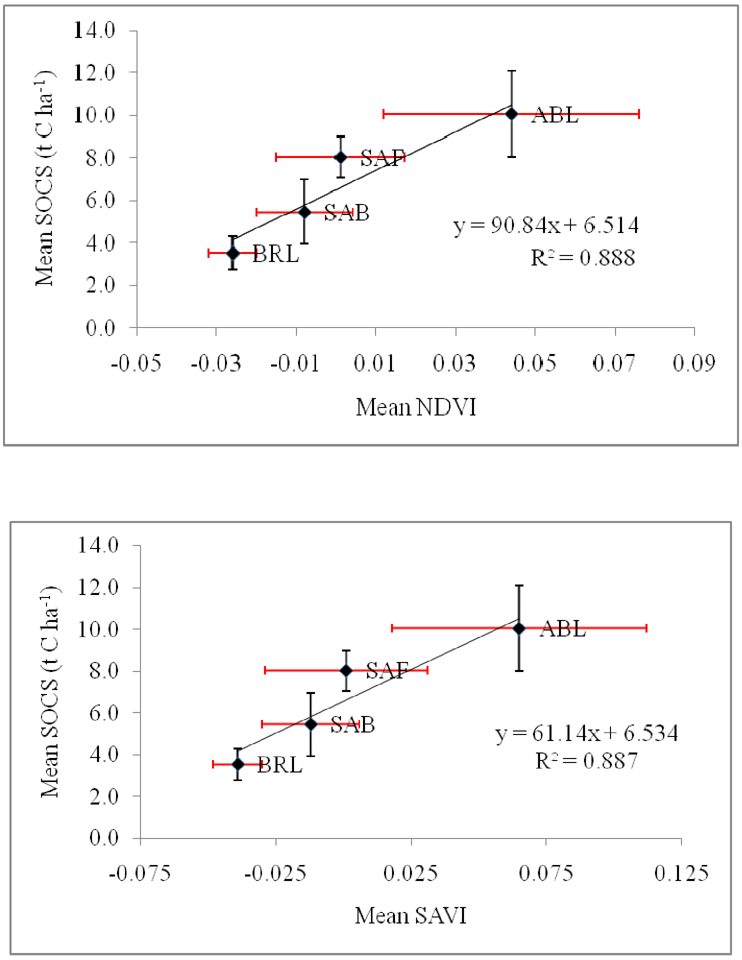

Figure 5 and 6. Relationship between the average means of SOCS (t C ha^{-1}) and the average means of normalized difference vegetation index (NDVI) and soil adjusted vegetation index (SAVI) of four vegetation cover types, respectively. BRL: bare land, SAB: sparsely distributed acacia with bare ground cover, SAF: sparsely distributed acacia with forb undergrowth and ABL: acacia bushland cover

semi-arid environments since vegetation is considered as a major source of SOCS inputs in such regions. The influence of varying soil backgrounds on the spectral reflectance was compensated by the adjustement factor, *n* (0.5) in the SAVI.

4.5. Synthesis

Based on the ANOVA, the means of SOCS and SOC concentrations at a depth of 0-15 cm were significantly different under each of the four different vegetation cover types studied (here it was higher in ABL and lower in BRL, with intermediate values for SAF and SAB). Vegetation cover type explained 85% of the variability in SOCS, 86% of the variability of SOC concentrations, while in the simple linear regression analyses, up to 89% spatial variability of SOCS can be related to both NDVI and SAVI in the *'rage'* grazing unit. Consequently, both hypotheses that SOCS and SOC concentration differed with vegetation cover types and that vegetation index (NDVI and/or SAVI) can be used useful tools to relate SOCS and vegetation cover types is accepted in the current study. These findings indicate that vegetation cover type alone can be a useful tool to roughly estimate the SOCS in the ASALs of northern Kenya. It also implies that such a relationship is of greater importance in assessing carbon inventory, especially in vast areas characterized by heterogeneous vegetation and terrain, as vegetation cover types are relatively easy to be identified, measured and categorized rapidly through satellite imagery and ground-truthing (remote sensing technology). Additionally, quantification of SOCS under different vegetation cover types and its relationship with NDVI and SAVI can also allow better estimates of carbon losses or increase to the atmosphere as vegetation cover type changes over time. However, it should also be noted that vegetation cover types alone as assessed in the present study cannot solely fully explain the behaviour of SOC concentration and SOCS. There is need to consider the effect of grazing intensity, animal contribution to spatial SOC redistribution in the grazing unit through defecation (manure deposits), site specific soil type information and profile attributes in order to quantify specific amounts of carbon sequestered into the soil by plants only (vegetation type). It could also be necessary to carry out the same research in the same rangeland during the rainy season to compare the results of dry and wet seasons.

Some limitations related to categorizing vegetation cover types, estimating SOC concentration and soil bulk density were encountered during the field work. The intensity of drought, which was very high at the time of data collection, may have impeded the existents of different vegetation cover types in the *'rage'* grazing unit with complete absence of grasses while acacia trees formed the main dominant vegetation type, with their densities varying across the rangeland.

Soil sampling for determination of SOC and soil bulk density was only possible to a depth of 0-15 cm, beyond which hard rocky material made it difficult to sample deeper under BRL and SAB. However, under ABL and SAF, it was possible to take samples to a depth of 0-30 cm, but for reasons of uniformity, soil sampling was only done to a depth of 0-15 cm. Landsat 5 TM satellite imagery, with a resolution of 30 m by 30 m used for characterizing vegetation cover types, did not yield a clear distinction between the different vegetation cover types. It is, therefore, recommended that a satellite image with high spatial resolution, e.g., of <5 m, like the IKONOS, Quickbird and SPOT HRV be used in future to obtain clear information on vegetation types, particularly in areas characterized by patchy vegetation growth, for the purposes of accurate estimation of the relationship between SOCS and vegetation types.

CONCLUSIONS AND RECOMMENDATIONS

Soil organic carbon stocks and SOC concentrations were significantly different under the four vegetation cover types at the depth of 0-15 cm. Soil bulk densities under BRL and SAB were similar but differed from those of ABL and SAF that were alike. The SOCS had high positive correlations with both the NDVI and SAVI, indicating that as NDVI and SAVI increased, SOCS will also increase. It is speculated in the present that the differences in SOC concentration and SOCS were related to the chemical composition and relative rates of organic carbon (litter) incorporation into the soil. Vegetation indices like NDVI and SAVI derived from satellite data can be employed to indirectly as a tool to relate SOCS and vegetation cover types in the rangelands of northern Kenya.

From the study, it is recommended that;

(i) A satellite image with a higher spatial resolution, e.g., of < 5m, like the IKONOS, Quickbird or SPOT HRV should be used instead of the Landsat 5 TM image for purposes of obtaining accurate identification of different vegetation cover types.

(ii) The effect of grazing intensity on, and animal contribution to, spatial redistribution of SOC in the grazing unit through pattern of defaecation (i.e., manure deposits), site specific soil information and profile attributes should be studied to quantify specific amounts of carbon sequestered by plants only (i.e., vegetation cover type).

(iii) A similar study should be undertaken on the same grazing unit *(‘rage’)* during the rainy season to compare the results of dry and wet seasons.

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