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Research and Full Length Article:

Projected Changes in Soil Organic Carbon Stocks over a 50-Year Period under Different Grazing Management Systems in Semi-Arid Grasslands of Kenya

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Abstract. Rangeland cover approximately 85% of Kenya's land mass and is a major resource for livestock farming with a considerable potential to mitigate climate change, yet these lands are stressed differently by various management. Our study aimed at predicting the long-term changes in Soil Organic Carbon (SOC) in grazing lands of Kenya under different grazing management systems (rotational, continuous and ungrazed), for a 50-year period using RothC 26.3. This research was conducted on a commercial grazing ranch which practices the two grazing management systems. Soil samples were collected at the depths of 0-10, 10-20 and 20-30 cm for the determination of soil organic carbon concentrations and bulk densities, results were later used for running the RothC model. The predicted results showed that the rate of SOC stock [t/ha] was higher under rotational grazing system in comparison to ungrazed and continual grazing system for the modelling period of 2015-2064. In the absence of grazing, the system was predicted to accumulate 19.22 Mg C ha^{-1} of SOC at the rate of 0.369 Mg C $ha^{-1}yr^{-1}$, whereas rotational grazing system was predicted to accumulate 30.46 Mg C ha^{-1} at the rate of 0.61 Mg C $ha^{-1}yr^{-1}$. The continual grazing management system resulted in the accrual of 18.49 Mg C ha^{-1} at the rate of 0.37 Mg C ha^{-1} yr^{-1} over 50 years. Thus, rotationally grazing management system have the potential of accumulating soil organic carbon in semi-arid grasslands.

Key words: RothC, Rangelands, Grazing systems, SOC

Introduction

Rangelands make approximately 50% of the global landmass and about 69% of the world's agricultural land (Faostat, 2009). Apart from being vital for domestic livestock production, rangelands are also important habitats for wild flora and fauna (Bolwig *et al.*, 2010; Galvin, 2009). The major use of drylands is for livestock production, mainly through pastoralism and ranching system. An estimated 25 million pastoralists and 240 million agro-pastoralists primarily depend on livestock production for their income (FAO, 2009). Livestock movement is the central component of land management (Galvin, 2009).

Soil forms the largest terrestrial reservoir of carbon (C) and can store about three times as much C as the atmosphere can sequestered mainly in decomposed plant litter and residues. Recently rapid losses of soil C associated with intensive livestock grazing have been reported for tropical savannah. Milchunas (2006) in his studies review reported that, the impact of grazing management on the soil biogeochemical processes that regulate rangeland carbon dynamics is not well understood due to heterogeneity in grassland types (Milchunas, 2006), out of the 34 data sets he evaluated to compare soil carbon of grazed and protected areas, about 40% indicated an increase in soil carbon due to grazing and about 60% showed a decrease or no response to grazing (Milchunas, 2006). Studies are done previously showed that the impact of grazing on ecosystem processes is influenced by the extent of the removal of photosynthetic biomass (defoliation), which is determined in part by grazing intensity; treading and trampling and faecal and urine depositions (Heitschmidt *et al.*, 2004). Repeated grazing reduces plant growth and productivity, whereas light-to-moderate levels cause suppression of growth with occasional growth enhancement (Green *et al*, 2000). Selective defoliation modifies species composition, that often leads to low productivity and undesirable plant compositions, hence affecting plant litter quality and consequently soil fertility. The livestock hoof action deteriorates soil aggregate stability and compacts the soil surface through trampling and treading leading to an increase in the soil bulk density. The unfavourable changes in soil physical properties may cause a decline in water infiltration and root growth. Livestock also influences the soil biogeochemical processes through the addition of nutrients in the form of faecal and urine. Barger *et al.*, (2004) in their studies reported that grazing has the potential to influence rangeland carbon dynamics by altering plant litter chemistry, litter production, plant biomass allocation patterns, and the spatial distribution of nutrients (Evans *et al.*, 1997). Furthermore, Welker *et al.*, (2004) reported that, depending on the intensity, grazing pressure may slow decomposition rates by decreasing plant litter carbon to nitrogen (C: N) ratio, or due to decreased standing biomass, may accelerate the decomposition by increasing soil temperature.

In the present time, it is essential to estimate the mitigation potential of grazing lands because of their vast area. There are several methods of estimating changes in soil organic carbon. The IPCC Guidelines (IPCC, 2006) provide a three-tiered approach where tier 3 is based on a dynamic model if the data is available. Models of soil organic carbon dynamics are a well-known tool to simulate the response of the soil system to environmental disturbances and are widely used to study changes in SOC stocks (Peltoniemi *et al.*, 2007). The main characteristics of the most popular process-oriented SOC turnover models have been discussed frequently in the literature (Wang *et al.*, 2013). From literature, it has been observed that the CENTURY, RothC and DNDC are the most frequently used models to simulate SOC dynamics spatially (Yu *et al*, 2003). RothC- 26.3 was originally developed and parameterized to model the turnover of organic C in arable top soils from the Rothamsted long-term field experiments. Later, it was extended to model the turnover in the grassland and in woodland, and operate in different soils under different climates (Coleman *et al.*, 1997). RothC-26.3 has been tested against long-term experiments in a range of soils and climatic conditions in Western and Central Europe and some parts of Africa (Coleman *et al.*, 1997; Falloon *et al*., 2002).

Currently, there are few experimental data regarding the potential for carbon sequestration in tropical drylands, particularly for the land management practices associated with grasslands (Farage *et al.*, 2007; Favretto *et al.*, 2016). Although field experimentation is required to confirm the ability of particular soils and agricultural practices to sequester carbon, modelling provides a means by which the overall feasibility of a variety of land management practices can be assessed (Smith *et al.*, 2010). Modelling soil carbon dynamics also provides a vehicle by which the most promising methodologies can be selected for further investigation. This is particularly relevant to soil carbon sequestration as it can take several years before measurable changes are evident in the field following alteration in agricultural practice (Poussart *et al.*, 2004; Rasmussen *et al.*, 1998). This study investigated the potential for carbon sequestration under different grazing management systems in semi-arid grasslands of Makueni County, Kenya using RothC modelling approach over a period of 50 years.

Materials and Methods

Site description

The study was conducted in Yaoni ranch located in Makueni County, approximately 125 km southeast of Nairobi, Kenya (Fig 1).

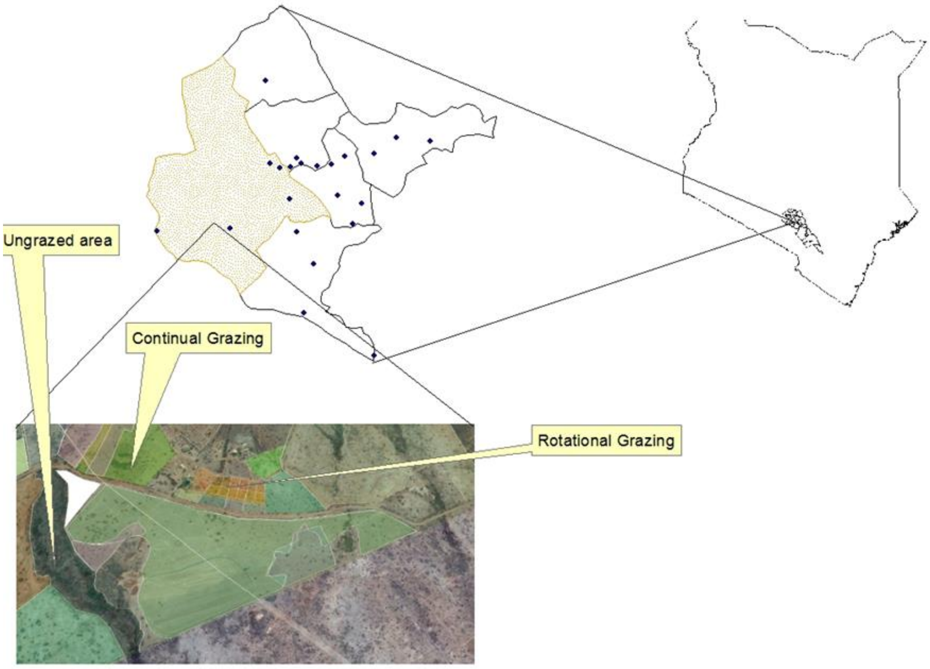

Fig. 1. Map of Kenya showing study

The county borders several counties which include Kajiado to the West, Taita Taveta to the South, Kitui to the East and Machakos to the North. It lies between Latitude 1º 35´ and 30 00´ South and Longitude 37º10´ and 38º 30´East.

The area lies at an altitude of between 1200-1400 m above sea level and receives bimodal rainfall with long rains falling between the months of March to May and short rains in October to December. Total annual rainfall is between 400 and 600mm. In between the rainy seasons, the area experiences intervening dry spells in January/February as well as July to September (Fig. 2)

The county is largely arid and semi-arid and usually prone to frequent droughts. The study site falls under agro-ecological zone IV and V. In terms of agro-ecological potential, classifies the area as a ranching zone naturally suited for extensive livestock production and wildlife.

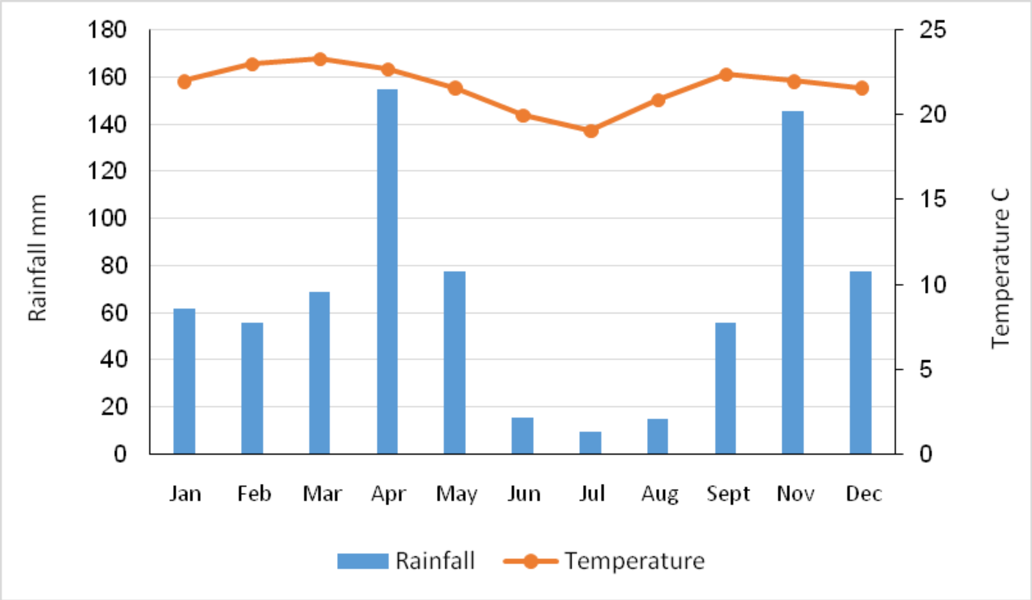

Fig. 2. Averages of rainfall and temperature data of Makueni County, Nairobi, Kenya from 1950-2014)

Experimental Design

The experimental design was a completely randomized design (CRD) involving two grazing systems and ungrazed area: continuous grazing, rotational grazing and ungrazed area grazing (control). This research site was on a commercial grazing ranch, which practices both rotational and continuous grazing. Within the same ranch, there was a section with similar geomorphology and soils as the rotationally grazed which was not converted and has been continuously grazed for over 30 years to represent the continuous grazing system. Under rotational grazing, a large herd of livestock is moved between paddocks for short periods of time. The ungrazed area consists of an abandon section of the ranch for more than 30 years due to a deep gully which was formed by gully erosion creating an isolated area inaccessible by livestock

Soil measurements

Nine representative spots per grazing system were randomly selected. For each spot, a soil profile was dug using pick axe and a shovel. Thereafter, the soil was sampled at intervals of 0–10, 10-20 and 20-30 depth using a soil auger. The samples were packed in a well level polythene bags for transportation. In addition, undisturbed soil samples for each depth were collected using core rings with a defined volume (100 cm^3) from each sampling plot for bulk density determination.

Samples were brought to ILRI Mazingira Centre in an airtight bag for analysis. The soil samples were air-dried and passed through a 2 mm sieve. In order to determine soil total C and N content, 20 g of sieved soils were dried at 40°C for 48hrs and thereafter ground with a hammer mill (Retsch M400Mixer Mill, Retsch GmbH, Germany). An about 20g subsample was then analysed for C and N concentrations using a high-temperature oxidative combustion system (Elementar Vario Max Cube). The bulk density for each depth was estimated by the core method (Blake, 1965).

Soil carbon stocks were calculated following equation 1:

$$\text{SOC Stock} = c \times BD \times D$$

Where:

SOC is the soil organic carbon stock (Mg C ha^{-1});

C= 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 (m)

Litter collection and carbon content determination

We used the quadrat method (Garg *et al*., 1975) to collect litter samples. In each plot, a 100 m^2 sub- plot was demarcated and five 1×1m quadrats laid out. A quadrat was placed at each of the four corners of the 100m^2 plot and the 5th quadrant placed at the center of the plot. There was a total of 135 quadrats used for the three grazing systems, each grazing system having 45 quadrats. Litter samples were collected from the 1×1m quadrats packed in well labelled bags. The litter samples were oven dried and thereafter ground with a hammer mill (Retsch GmbH, Germany). A 10g subsample was then analysed for C concentrations using a high-temperature oxidative combustion system (Elementar Vario Max Cube). The result was converted to T C/ha. Plant residue input was calculated by dividing this amount with the number of years the place has been under grazing to get the yearly residue input. Then divide by 12 to get the monthly residue input.

RothC model Description

The RothC-26.3 model is a SOM decomposition model that divides incoming plant residues into decomposable plant material (DPM) and resistant plant material (RPM); these both decompose to form microbial biomass (BIO), humified organic matter (HUM) and evolved CO2 (Coleman & Jenkinson, 1996). The model also includes an inert pool of organic matter (IOM). Roth-C is one of the most widely used SOC models (Jenkinson *et al.*, 1991; Juma *et al.*, 1996) and has been evaluated in a wide variety of ecosystems including croplands, grasslands, and forests (Falloon *et al*, 2002). The schematic structure of the Roth-C model (Fig 3) depicts plant residues entering the soil environment, undergoing decomposition by the soil microbial biomass to form several pools with the evolution of CO2.

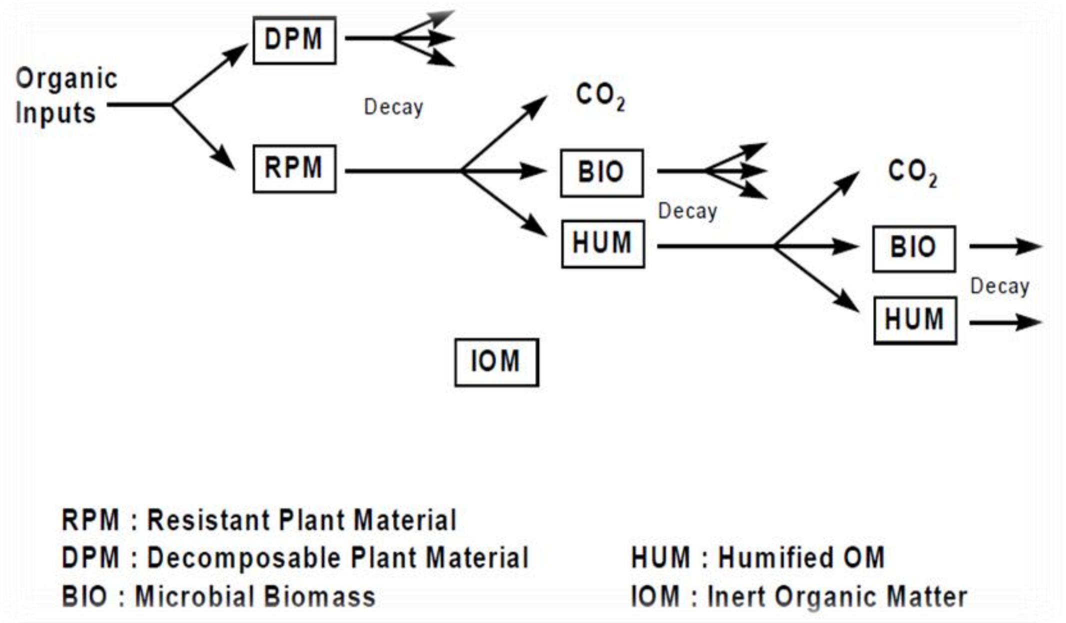

Fig. 3. The schematic structure of the Roth-C model

The Roth-C model requires three types of data:

a) Climatic data; monthly rainfall (mm), monthly evapotranspiration (mm), average monthly mean air temperature (° C);

b) Soil data; clay content (%), inert organic carbon (IOM), initial soil organic carbon (SOC) stock (t C ha-1), depth of the soil layer considered (cm);

c) Land use and land management data; soil cover, monthly input of plant residues (t C ha-1), monthly input of farmyard manure (FYM) (t C ha-1), residue quality factor (DPM/RPM ratio) (Jenkinson *et al.*, 1991).

RothC Model Calibration

For calibration, the RothC model was run through an equilibrium period (7000–10,000 years) standard procedure to represent soil and vegetation conditions prior to human disturbance (Parton *et al.*, 1987). The equilibrium files for all the land management units (monthly plant residue input, soil cover, monthly farm yard manure) were prepared. The model was set up to simulate the characteristics of the study site, including the land management represented by monthly C inputs (t C ha-1) and soil cover (Patra *et al.*, 1990) (whether the soil is covered by a crop or is fallow). All soil pool data were converted from g C/kg soil to t C/ha for use in the model.

Climate data for Makueni County were acquired from Kenya meteorological department. Land management data with a DPM/RPM (decomposable plant material/resistant plant material) ratio of 0.67 and an inert organic matter (IOM) content of 4.83, 4.55 and 3.798 t C ha^{-1} for ungrazed site, rotationally and continually grazed sites respectively were approximated using equation (1) proposed by Falloon *et al*, 1998 (because the radiocarbon content was not known) were used to simulate equilibrium land use at the study site.

IOM = 0.049TOC1.139 (1)

Where:

TOC =Total organic carbon, t C ha^{-1}

IOM = inert organic matter, t C ha^{-1}

Model input files were created using the input data collected from the site, and model runs executed to accurately simulate management regimes at the site studied.

Validation of Model

The model was validated using pools obtained from the calibration process. Data of carbon and radiocarbon values in all these compartments receiving in the equilibrium mode (initial soil carbon, initial radiocarbon values), were used to run the model in short term mode (for modelling of soil organic carbon in time period 1950-2014 for validation of RothC model, or from 2015-2064 for predicting soil organic carbon accumulation in future)

Running the model- Simulation procedure

The initial carbon content of the soil organic matter pools and the annual plant addition to the soil were obtained by running the RothC model to equilibrium under constant environmental conditions (Coleman & Jenkinson, 1996). The constant climatic conditions were taken to be the average of climate data from 1950 to 2010 By initializing the model in, and running the model from 1950, potential initialization effects are minimized (Smith *et al*., 2005). RothC is known to be relatively insensitive to the distribution of C inputs through the year; the proportions of plant material added to the soil in each month were set to describe the pattern of inputs for typical grassland (Table 1). Plant cover was assumed to occur all year round in grasslands. Initially, the total plant input was obtained by dividing litter carbon content by the number of years the area has been under the different management to get the annual plant residue input and by 12 to get the monthly plant residue input. This was not intended to represent the actual plant addition, but provided the first point in the initialization, indicating how the annual plant addition should subsequently be adjusted.

The adjusted annual plant addition was then redistributed through the months (Table1), and the equilibrium run repeated. This iteration was continued until the measured and the simulated carbon contents of the soil were within 0.00001 tC ha^{-1}. Having determined the plant additions and carbon contents of the soil organic matter pools, the simulations were run forward from 2015 to 2064 using the measured climate and simulated plant residue input data.

Table 1. The proportion of carbon (tCha-^{1}) assumed added in plant material each year under different grazing management systems based on RothC model calculations

Month	Rotation grazing	Continual grazing	Ungrazed
January	0.05	0.015	0.022
February	0.05	0.015	0.022
March	0.05	0.015	0.022
April	0.05	0.015	0.022
May	0.10	0.037	0.050
June	0.15	0.037	0.050
July	0.10	0.037	0.050
August	0.15	0.037	0.050
September	0.10	0.035	0.050
October	0.10	0.035	0.050
November	0.05	0.035	0.020
December	0.05	0.035	0.020

Results and Discussion

Influence of grazing on soil bulk density, carbon concentration

Results for soil bulk density, soil organic concentrations and stocks are presented in Table 2. The results showed that, along the soil sampling depths, we observed a significant difference ($p \leq 0.05$) in soil bulk density with continuously grazed site showing the highest values followed by rotationally grazed and ungrazed area, respectively. However, there was no significant difference in bulk density at the lower across the management regimes. In our study, the low bulk density in the ungrazed area can be attributed to the lack of grazing disturbance from livestock, while the lower bulk densities in rotational grazing compared to continual grazing sites can be attributed to the minimum livestock impact (Tuffour *et al.*, 2014) and loafing (Wang & Batkhishig, 2014) due to short duration grazing that gives maximum rest to the grazed area. The higher soil bulk density in continuous grazing sites, on the other hand, is probably a result of soil compaction due to continuous grazing (Curran Cournane, 2010; Wolf, 2011).

Table 2. Soil bulk density (gcm-^{3}), carbon concentrations (%) and stocks (MgC ha-^{1}) under different grazing management systems

	Depth(M)	Continuous	Rotational	Ungrazed
Soil bulk density (gcm-^{3})	0.0-0.1	1.57±0.02a	1.45±0.01b	1.22±0.02c
	0.1-0.2	1.46±0.04a	1.38±0.04b	1.17±0.02c
	0.2-0.3	1.28±0.01a	1.24±0.01b	1.13±0.02c
SOC concentrations (%)	0.0-0.1	1.196±0.16 b	1.445±0.09a	1.711±0.12 a
	0.1-0.2	1.031±0.06 c	1.341±0.02b	1.648±0.11a
	0.2-0.3	0.933±0.01b	0.933±0.08b	1.401±0.17a
SOC Carbon stocks (MgCha-^{1})	0.0-0.1	18.66±2.82 a	20.90 ±1.83 a	20.95±1.43a
	0.1-0.2	14.95±2.00 c	18.85±0.51a	19.42±1.65a
	0.2-0.3	11.97±2.41b	13.67±2.11ab	15.93±4.73a

Means with different letters within the row are significantly different ($P \leq 0.05$)

The ungrazed site showed higher SOC concentrations and stocks than the grazed sites in all the sampling depths (Table 2) respectively. Similarly, the rotationally grazed site showed higher SOC concentrations and stocks along the entire sampled soil depths compared to continual grazing system. However, the difference in SOC concentration was not statistically different in ($p \geq 0.05$) across the three sites for the upper soil layer (0-0.1 m). Significant differences ($p < 0.05$) in SOC concentration were found across sites for the 0.1-0.2 m and 0.2-0.3 m depths, respectively. These results showed that continual grazing depresses SOC content and storage that is in accordance with some previous studies (Snyman *et al*, 2005; Wu *et al.*, 2010). Also, the observation from this study demonstrated higher SOC concentrations and stocks in a rotationally grazed site than in a continually grazed area for all the sampled soil depths. The differences in soil carbon concentrations and stocks can be attributed to the influence of grazing animals on soil bulk density and vegetation dynamics.

Projected influence of grazing management on soil organic carbon stocks.

The results of predicted soil organic carbon stocks are presented in Fig 4. Results show that, in the absence of grazing, the site was predicted to accumulate 19.22 Mg C ha^{-1} of SOC at the rate of 0.369 Mg C ha^{-1}yr^{-1}, whereas rotational grazing system was predicted to accumulate 30.46 Mg C ha^{-1} at the rate of 0.61 Mg C ha^{-1}yr^{-1} .The continual grazing management system resulted in the accrual of 18.49 Mg C ha^{-1} at the rate of 0.37 Mg C ha^{-1} yr^{-1} over 50 years. Thus, all the grazing treatment was predicted to accumulate SOC.

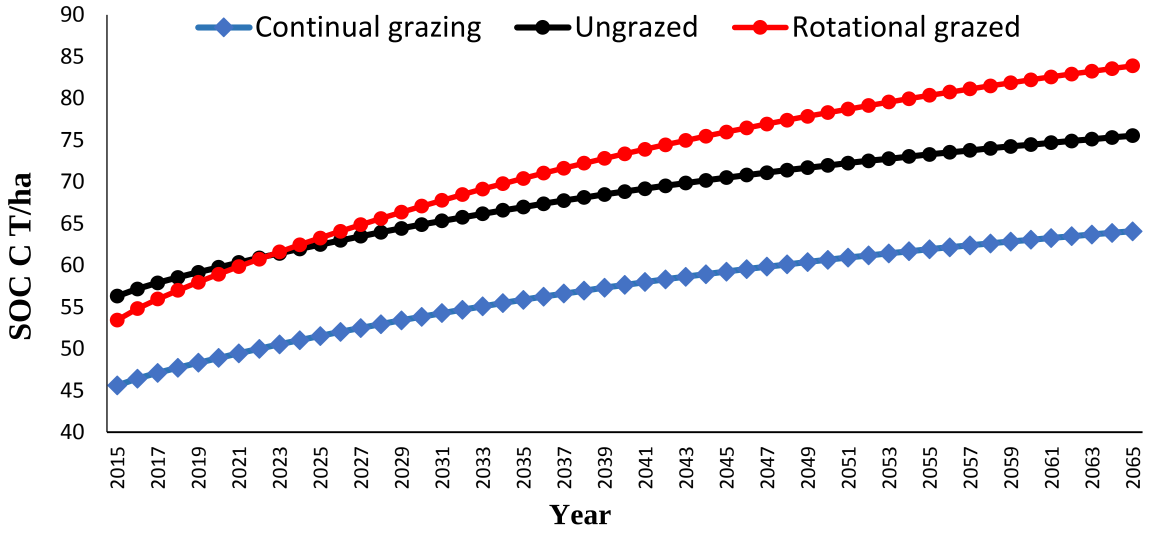

Fig. 4. Predicted Soil organic Carbon Stocks for a 50-year period under different grazing management systems

The predicted higher SOC sequestration in rotationally grazed area than in both continual and ungrazed areas can be due to several reasons. First, plant biomass returning into the soil is the major factor. Under the rotational system, the input of above-ground plant materials is basically continuous throughout the year in a significant amount compared to continually grazed areas. This can be attributed to enhanced biomass production due to higher forage recovery time under rotational grazing management. Areas under continual grazing have little litter input to the soils due to the impact of livestock grazing continuously until forage becomes insufficient to sustain them hence exposing plants to frequent defoliation, (Kamau, 2003; Kioko *et al*., 2012; Lemus *et al*., 2011; Metera *et al*., 2010) thus the production of less litter consequently leading to low soil organic carbon accumulation. The predicted difference in soil organic carbon across the grazing systems can also be attributed to the difference in the herbaceous vegetation cover. The higher aboveground standing biomass under rotational grazing and ungrazed sites significantly reduce the loss of organic matter and nutrients from the soil-plant system through soil erosion. Also, more stubble biomass is expected under rotational grazing sites than continual grazing sites, which means a conversion of the atmospheric carbon through the process of photosynthesis into carbon and nitrogen compounds that are returned to the soil through litter fall and dead plant materials. The predicted higher soil carbon accumulation in the rotational grazing management system can, therefore, be attributed to increased aboveground biomass. Our modelling results indicate a higher proportion of total plant material in rotational grazed systems entering into the soil for carbon sequestration compared with both continually grazed and ungrazed areas.

Furthermore, the effect of grazing livestock on soil physical characteristics can explain the differences in the predicted high accrual of soil carbon between the areas under rotational and continuous grazing systems. The predicted low rate of accumulation of soil organic carbon under continual grazing system can be due to livestock trampling as a result of high grazing pressures. Trampling disrupts soil aggregates, which protect soil organic matter from decomposition (Six *et al*., 1999), they stimulate short-term microbial activity through enhanced aeration, resulting in increased emissions of CO_2 and other radioactive gases to the atmosphere (Bayer *et al.*, 2002; Kladivko, 2001). Furthermore, the trampling mixes fresh residues into the soil where conditions for decomposition are often more favourable than on the surface. The less disturbed soils under rotational and ungrazed sites pasture contribute positively to soil carbon sequestration.

The predicted high accumulation rates of soil organic carbon stocks can also be due to better microclimates in rotational grazing and ungrazed sites that result from adequate herbaceous cover and woody vegetation respectively which reduces the soil temperatures and evapotranspiration rates. The low herbaceous plant cover under the continual grazing system as a result of high grazing pressure exposes soils to sun rays leading to increased soil temperatures and evapotranspiration rates hence increases the decomposition of organic matter resulting in higher losses of carbon from the soil (Tom *et al.*, 2006). Furthermore, the presence of deep-rooted plants (trees) that gradually decompose when the plant dies in combination with leaf litter decomposition may have contributed to high SOC in ungrazed and rotationally grazed area than in continually grazed area. A few shrubs, kinds of grass and herbs with shallow roots contribute to annual litter deposition that is also suppressed by herbivores and this resulted in low SOC accumulation in the area under continuous grazing.

Under the scenarios considered, soil physical, chemical and biological properties would probably change due to alterations in the quantity and quality of C inputs to the soil, nutrient changes and stimulation of decomposition. Some of the issues discussed here are in agreement with the general patterns reported in other point or site scale studies. Fearnside and Barbosa (1998), for example, showed that trends in soil C were strongly influenced by pasture management. Sites that were judged to have been under poor management generally lost soil carbon, whereas sites under good management accumulated soil carbon. Some studies have showed that, degraded pastures with little grass cover are less likely to accumulate soil C because inputs to SOC from pasture roots will be diminished. Greater grazing intensity and soil damage from poor management would, in all likelihood, cause soil C losses or low rate of accumulation, which explains the low soil organic carbon stocks accumulations under continual grazing system in our study. Barger in his studies reported that grazing has the potential to influence rangeland carbon dynamics by altering plant litter chemistry (Barger *et al.*, 2004), litter production, plant biomass allocation patterns, and the spatial distribution of nutrients (Evans *et al.*, 1997). Furthermore, he reported that, depending on the intensity, grazing pressure may slow decomposition rates by decreasing plant litter carbon to nitrogen (C: N) ratio, or due to decreased standing biomass, may accelerate the decomposition by increasing soil temperature (Welker *et al.*, 2004).

Conant *et al* (2001) in their study, showed that the major factor controlling soil organic carbon dynamics is actually grazing management, he found that soil organic carbon averaged 8.4 Mg C ha^{-1} more under intensive management or short rotation grazing than extensively grazed or hayed sites. Naeth *et al.* (1990) observed a negative impact on soil organic matter with heavy intensity or early season grazing, as compared to light intensity or late season grazing in the grasslands of Alberta, Canada. Heavy grazing resulted in significant reductions in the height of standing and fallen litter, and a decrease in live vegetative cover and organic matter mass. Our results disagree with the study done by R. Gill (2007). For instance, Gill (2007) in his evaluation of the influence of 90 years of protection from grazing on carbon dynamics in subalpine rangeland, reported that livestock grazing had no significant impacts on total soil carbon or particulate organic matter, but active soil carbon content increased and that the loss of carbon from the active carbon pool was higher in grazed sites than in ungrazed areas. The implication of these results is that grazing may convert the relatively recalcitrant carbon pool into easily mineralizable carbon fraction.

Conclusion

Our results showed that the RothC can adequately simulate SOC under different grazing management provided a correct proportion of plant residues are used as soil carbon input. It is estimated that soil carbon in rotationally grazed systems can sequester 6.5 t C over 50 years, yielding an average 0.46 t C ha^{-1} $year^{-1}$ in a medium rainfall region. In the absence of grazing, the system was predicted to accumulate 19.22 Mg C ha^{-1} of SOC at the rate of 0.37 Mg C $ha^{-1}yr^{-1}$, whereas the continual grazing management system resulted in accrual of 18.49 Mg C ha^{-1} at the rate of 0.37 Mg C ha^{-1} yr^{-1} over 50 years. Thus, all the grazing treatment were predicted to accumulate SOC. The difference in the predicted SOC accumulation can be attributed to effects of grazing livestock on soil physical, chemical and biological properties which would probably change due to alterations in the quantity and quality of C inputs to the soil. The results highlighted the importance of well-managed pasture for soil carbon sequestration as a potential measure for mitigating climate change.

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