COMPLEMENTARY EFFECTS OF LEGUME INTEGRATION AND FERTILIZER APPLICATION ON SOIL MOISTURE AND LONG-TERM CARBON STOCKS IN MAIZE SYSTEMS OF KABETE SUB-COUNTY, KENYA †

[EFECTOS COMPLEMENTARIOS DE LA INTEGRACIÓN DE LEGUMBRES Y LA APLICACIÓN DE FERTILIZANTES SOBRE LA HUMEDAD DEL SUELO Y LAS ACCIONES DE CARBONO A LARGO PLAZO EN LOS SISTEMAS DE MAÍZ DEL SUBCONDADO DE KABETE, KENIA]

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SUMMARY

Background. Despite their immense benefits to smallholder farmers, the complementary effects of combined fertilizer sources with integration of legumes on soil moisture, soil organic carbon content, carbon stocks and their long-term projections in maize systems of Kabete sub-County, Kenya has not been fully investigated. This study will thus develop and promote a site specific technological package that will enhance maize productivity, resilience and sustainability of the smallholder farming systems. **Objective**. To determine the complementary effects of legume integration and fertilizer application on soil moisture and soil carbon stocks, and carbon stock changes over a 20-year period in maize systems of Kabete sub-County, Kenya. **Methodology.** The experiment was conducted at Upper Kabete field Research Station of the University of Nairobi during the long (LRS) and short (SRS) rainy seasons of 2015/2016. The experimental design was a Randomized Complete Block Design with a split plot arrangement. The main plots were integration of dolichos into maize (Z*ea mays L.*) systems; (i) as an intercrop (dolichos - *Lablab purpureus* (L.)/maize) and (ii) in rotation (dolichos-maize), and (iii) sole maize (without dolichos integration). The sub plots were organic and inorganic fertilizers: (i) Farmyard Manure (FYM), (ii) Triple Superphosphate (TSP)+Urea, (iii) FYM+TSP+Urea and (iv) no fertilizer input (control). Soil samples were collected at the end of each cropping season from 0-20 cm depth for determination of; soil moisture (%), soil organic carbon (SOC) content (%), and SOC stocks (t C ha^{-1}). The Rothamsted Carbon model (Roth-C) was used to estimate carbon stock changes over a 20-year period with 1990 as the base year. **Results.** Significantly ($P \leq 0.05$) high levels of soil moisture (31 and 30.1%) and SOC (2.6 and 2.5%) were respectively obtained in maize/dolichos intercrop with application of FYM and FYM+TSP+Urea during the SRS. The same trend in soil moisture and SOC was observed in the LRS. Significantly ($P \leq 0.05$) high SOC stocks (t C ha^{-1}) were obtained in maize/dolichos intercrop with FYM (56.20 and 54.71) and TSP+FYM+Urea (54.84 and 52.91) application in the SRS and LRS, respectively. Over a 20-year period, SOC stocks maintained a significant and steady increase and were higher in maize/dolichos intercrop with FYM and FYM+TSP+urea application. The same pattern was noted in dolichos-maize rotation and sole maize systems. **Implications.** Given the importance of SOC in the improvement of soil quality, incorporation of legumes into maize systems with application of FYM is thus a plausible technological package that could enhance soil fertility and consequently food and nutritional security among smallholder farmers, not only of Kabete sub-County but Kenya and other countries. **Conclusion.** Significant increases in soil moisture content, organic carbon and, carbon stocks and their projections over a 20-year period were evident in maize/dolichos intercrop with FYM and TSP+FYM+Urea application in both seasons.

Keywords: Farm Yard Manure; *Lablab purpureus* L.; Soil quality; Triple super phosphate; Roth-C; Urea; *Zea mays* L.;

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RESUMEN

Antecedentes. A pesar de sus inmensos beneficios para los pequeños agricultores, los efectos complementarios de las fuentes combinadas de fertilizantes con la integración de las leguminosas en la humedad del suelo, el contenido de carbono orgánico del suelo, las reservas de carbono y sus proyecciones a largo plazo en los sistemas de maíz del subcondado de Kabete, Kenia, no han sido completamente investigado Por lo tanto, este estudio desarrollará y promoverá un paquete tecnológico específico para el sitio que mejorará la productividad, la resistencia y la sostenibilidad del maíz de los sistemas agrícolas de pequeños productores. **Objetivo.** Determinar los efectos complementarios de la integración de leguminosas y la aplicación de fertilizantes sobre la humedad del suelo y las reservas de carbono del suelo, y los cambios en las reservas de carbono durante un período de 20 años en los sistemas de maíz del subcondado de Kabete, Kenia. **Metodología.** El experimento se realizó en la estación de investigación de campo de Upper Kabete de la Universidad de Nairobi durante las temporadas lluviosas largas (LRS) y cortas (SRS) de 2015/2016. El diseño experimental fue un diseño de bloques completos al azar con una disposición de parcela dividida. Las parcelas principales fueron la integración de dolichos en los sistemas de maíz (*Zea mays* L.); (i) como cultivo intercalado (dolichos - *Lablab purpureus* (L.) / maíz) y (ii) en rotación (dolichos-maíz), y (iii) maíz único (sin integración de dolichos). Las parcelas secundarias fueron fertilizantes orgánicos e inorgánicos: (i) Estiércol de corral (FYM), (ii) Superfosfato triple (TSP) + Urea, (iii) FYM + TSP + Urea y (iv) ningún aporte de fertilizante (control). Las muestras de suelo se recolectaron al final de cada temporada de cultivo de 0 a 20 cm de profundidad para determinar; humedad del suelo (%), contenido de carbono orgánico del suelo (SOC) (%) y reservas de SOC (t C ha-1). El modelo Rothamsted Carbon (Roth-C) se utilizó para estimar los cambios en las reservas de carbono durante un período de 20 años con 1990 como año base. **Resultados**. Se obtuvieron altos niveles de humedad del suelo (31 y 30.1%) y SOC (2.6 y 2.5%) respectivamente en cultivos intercalados de maíz / dolichos con la aplicación de FYM y FYM + TSP + Urea durante el SRS ($P \leq 0.05$). La misma tendencia en la humedad del suelo y el COS se observó en el LRS. Se obtuvieron reservas significativas ($P \leq 0.05$) de alto contenido de COS (t C ha-1) en cultivos intercalados de maíz / dolichos con FYM (56.20 y 54.71) y aplicación de TSP + FYM + Urea (54.84 y 52.91) en el SRS y LRS, respectivamente. Durante un período de 20 años, las existencias de COS mantuvieron un aumento significativo y constante y fueron mayores en el cultivo intercalado de maíz / dolichos con la aplicación de urea FYM y FYM + TSP +. Se observó el mismo patrón en la rotación de dolichos-maíz y en los sistemas de maíz único. **Implicaciones.** Dada la importancia del COS en la mejora de la calidad del suelo, la incorporación de leguminosas en los sistemas de maíz con la aplicación de FYM es, por lo tanto, un paquete tecnológico plausible que podría mejorar la fertilidad del suelo y, en consecuencia, la seguridad alimentaria y nutricional entre los pequeños agricultores, no solo del subcondado de Kabete sino todo Kenia y otros paises. **Conclusión.** Los aumentos significativos en el contenido de humedad del suelo, el carbono orgánico y las reservas de carbono y sus proyecciones durante un período de 20 años fueron evidentes en el cultivo intercalado de maíz / dolichos con la aplicación de FYM y TSP + FYM + Urea en ambas estaciones.

Palabras clave: Estiércol de corral; *Lablab purpureus* L .; Calidad del suelo; Triple superfosfato; Roth-C; Urea; *Zea mays* L;

INTRODUCTION

Sustainable agricultural production incorporates the notion that natural resources be used to increase agricultural output and income without depleting the natural resource base (Gruhn *et al.*, 2000). Recently, unsustainable land cultivation practices such as continuous soil cultivation without adequate nutrient replenishment has led to accelerated depletion of the natural soil base available for food production (Hossner and Juo, 1999). Woomer *et al.* (1994) opined that continuous cropping with its associated tillage practices provokes an initial rapid decline in soil organic matter (SOM) which then stabilizes at low levels. The dynamics of SOM is also influenced by agricultural management practices such as mulching, removal of crop residues, fertilization (Duiker and Lal, 1999) and legume integration in cropping systems (Onwonga et al., 2014). The smallholder farmers of central highlands of Kenya intercrop cereals with grain legumes, such as dolichos Lablab (Lablab purpureus (L.) as a strategy for diversifying food production and household income since legumes are both cash and food crops (Cheruiyot *et al.* 2001; Mafongoya *et al.*, 2006; Fenta *et al.*, 2014). Besides, intercrops efficiently utilize the natural resources such as land, light, water and nutrient and increase biodiversity, productivity, resilience and stability of agroecosystem (Ning et al. 2017).Legumes, whether intercropped or grown in rotation, can suppress the growth of weeds, recover deeply leached nutrients and add organic material to the soil, thus improving soil organic carbon (SOC) in agricultural soils (Nyambati *et al.*, 2006; Maass *et al.* 2010; Tautges et al., 2017).

The SOC stocks in agricultural land reflect the balance between the inputs from plant residues and animal waste and losses due to decomposition and erosion as in any other terrestrial ecosystem (Grace J. 2004; Adhikari and Hartemink 2016). The amount of plant residue derived C that enters the soil depends on the growth of the plants (net primary production) and the portion removed from the field as part of the harvested crop. Soil C return from plants consist of inputs from above-ground and below-ground (Bolinder et al. 2007, Heikkinen J. 2016). SOC is a universal indicator of soil quality, and variations in SOC levels can have serious implications on many environmental processes, such as soil fertility, erosion and GHG fluxes (Stolbovoy *et al*., 2007).

Agronomic practices aimed at improving SOC which is present as soil organic matter and reducing moisture stress offer greater potential benefits to sustainably improving crop productivity in rainfed agriculture (Lobell, 2008). Such practices often involve integration of legumes into cropping systems, combined use of inorganic and organic fertilizers among others (Vanlauwe et al., 2010; Sitienei et al., 2017). The application of sole animal manure applied or in combination with chemical fertilizers, improves soil organic carbon concentration (Manna *et al.,* 2007; Cong *et al.,* 2012). Whereas, application of farmyard manures to soil provide benefits such as soil fertility and structure improvement, increased soil organic matter, better water holding capacity and high organic carbon content (Sharif *et al.,* 2004: Onwonga et al., 2019).

Despite their palpable usefulness to small-scale farmers, the complementary effects of combined fertilizer sources with integration of legumes on soil moisture, soil organic carbon content, carbon stocks and their long-term projections in maize systems of Kabete sub-County, Kenya has not been fully investigated. Moreover, while most research, involving the use of models, related to C sequestration have been conducted in developed nations (Kukal 2009; Onwonga et al., 2018), comparatively fewer studies have been conducted on impact of fertilizer management practices and integration of legumes on soil carbon sequestration under different cropping systems in developing countries (Conen et al., 2003).
Due to the high costs of soil sampling and chemical analysis needed to report the SOC stock changes based on measurements (Conen et al., 2003; Mäkipää et al., 2008), models such as Roth-C thus becomes handy in estimating SOC stock changes. Modelling using Roth-C would therefore provide an opportunity to estimate and predict, in the short and long-term, SOC trends and sequestration in soil along with identifying land use and management practices with large potential for C sequestration (Wan *et al.,* 2011; Wang *et al., 2016)*.

The current study investigated the complementary effects of legume integration and, inorganic and organic fertilizer application on soil moisture and organic carbon, and carbon stocks and trends over a 20-year period in maize systems (Z*ea mays L.*) of Kabete sub-County, Kenya

MATERIALS AND METHODS

Site Description

The field experiment was conducted at upper Kabete field research station of the University of Nairobi, located about 10 km north of Nairobi, during the long rainy seasons (LRS) of 2015 and short rainy seasons (SRS) of 2015/2016. The field station is about 1940 m above sea level, at a latitude of 1°15’S and longitude 36°41’E and is categorized under agroecological zone III (Jaetzold *et al*., 2006). The climate is typically sub-humid with minimum and maximum mean temperatures of 13.7°C and 24.3°C, respectively. The site has a bimodal rainfall distribution (long rains - mid-March to May and short rains - October to December). The average annual precipitation is 1000 mm (Jaetzold *et al*., 2006). Figure 1 shows the amount of rainfall received during the experimental period.

Soils of the research site are predominantly deep red humic nitisols containing 60-80% clay particles (KSS, 2004; WRB, 2006). The measured initial soil characteristics (0-20 cm depth) were; clay texture, moderate acidity, moderate organic carbon, moderate nitrogen, high potassium and low available P levels (Table 1) according to Landon (1991) soil nutrient classification method.

The main crops grown in the LRS include maize, potatoes, beans, carrots, tomatoes and limited temperate fruits such as avocados and grapes. Maize, often intercropped with beans, dominates the cropping pattern. Of the whole households’ population in the County, 44% derive their income from agriculture while 45% rely on urban self-employment (FAO, 2007).

Experimental Design and Treatments

The on-station field experiment was conducted during the LRS of 2015 and SRS of 2015/2016. The experimental design was a RCBD with a split plot arrangement. The main plots (4.5m x 8.2m) were integration of dolichos in a maize crop system (i) as an intercrop (dolichos - *Lablab purpureus* (L.)/maize) and (ii) in rotation (dolichos-maize), and (iii) sole maize. The sub plots (4.5m x 2.4m) were fertilizer types: (i) Farmyard manure (FYM), (ii) Triple superphosphate (TSP) and urea, (iii) FYM+TSP+Urea and (iv) no fertilizer input (control).

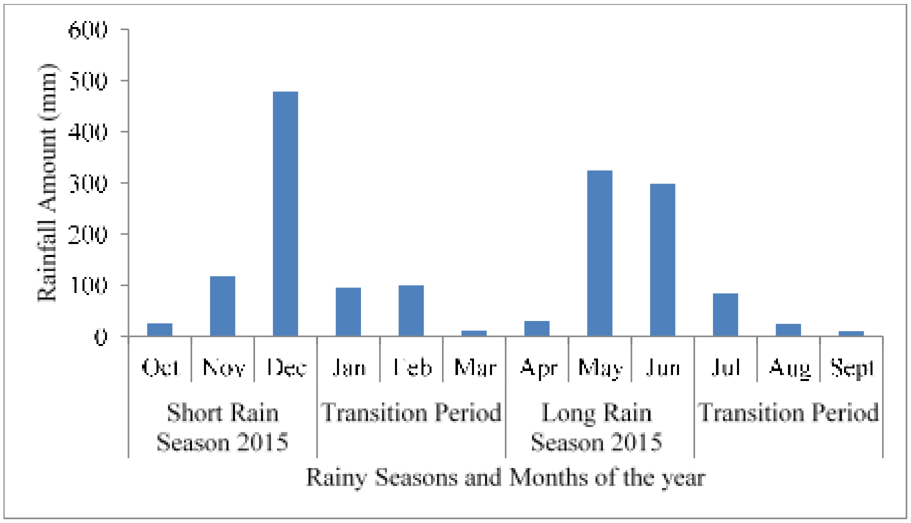


Figure 1. Total monthly rainfall received during the experimental period (mm).

Table 1. Initial physical and chemical soil properties at experimental site (0-20 cm depth)

Soil property	Units	Value	Soil Property	Units	Value
Soil pH (H_20)	-	6.1	Ca	$Cmol_cKg^{-1}$	8.2
Soil pH ($CaCl_2$)	-	5.7	Mg	$Cmol_cKg^{-1}$	1.6
Available P	Mg Kg^{-1}	11	% Sand	%	6
Total N	%	0.28	% Silt	%	27
Organic C	%	1.96	% Clay	%	67
Potassium	$Cmol_cKg^{-1}$	1.07	Textural Class	-	Clay

Agronomic practices

Tractor drawn moldboard plow was used in primary land preparation. In secondary cultivation, which involved leveling the ground, hand hoes were used. FYM (5 and 10 t ha^{-1}- Table 2) was added a week to planting in planting holes. The combined TSP and Urea (60 kg ha^{-1}) were placed in planting holes (banding) about five cm deep at planting for both seasons.

Planting was done by placing seeds directly into the soil. Two maize seeds (Duma 43 variety) were planted per hill at a depth of about 0.05m with a spacing of 0.75 by 0.30m in respective treatments. In the rotation system, two seeds of dolichos were planted at a depth of about 0.05 m with a spacing of 0.75 by 0.3m. For the intercrop system, dolichos was planted in between maize rows at the same inter-plant spacing as in pure stands at the start of the LRS of 2015 and SRS of 2015/16. Sole dolichos was planted during the LRS and rotated with maize in the SRS. Thinning to one seedling per hill was done four weeks after planting. Weeding was done by hand hoeing at 3 weeks after germination and at the flowering stage. Figure 2 show maize at tasseling and dolichos crop at flowering stages.

Soil sampling and analysis

Determination of soil moisture and soil organic carbon. Soil samples for moisture and organic carbon content determination were collected at 0.2m depth between plants in a row in every plot, using a 5 cm diameter soil auger at harvest time of each cropping season. Soil moisture and soil organic carbon contents were determined using the gravimetric method (Black, 1965) and Walkley-Black wet oxidation method (Nelson and Sommers, 1982), respectively.

Determination of soil organic carbon stocks. The samples for determination of soil organic carbon stocks (calculated per unit area at a given depth) were collected, using a 5cm soil auger, near plant roots to a depth of 0.2m. In addition, a ring sampler was used to collect soils for the measurement of soil bulk density. Bulk density was estimated using the core ring method after oven-drying a specific volume of soil at 105^0C for 48 h (Blake 1965). Soil organic carbon stock (SOC) was calculated using the formulae; SOCS (t Cha^{-1}) = $\rho_s xHxC$ (Bernoux *et al.*, 1998).

Where; p_s, is the soil bulk density (g cm^{-3}); H is the thickness of the sampled soil layer (cm) and C is the carbon content in the soil (%).

Figure 2. Maize and dolichos test crops at tasseling and flowering stages, respectively during the experiment.

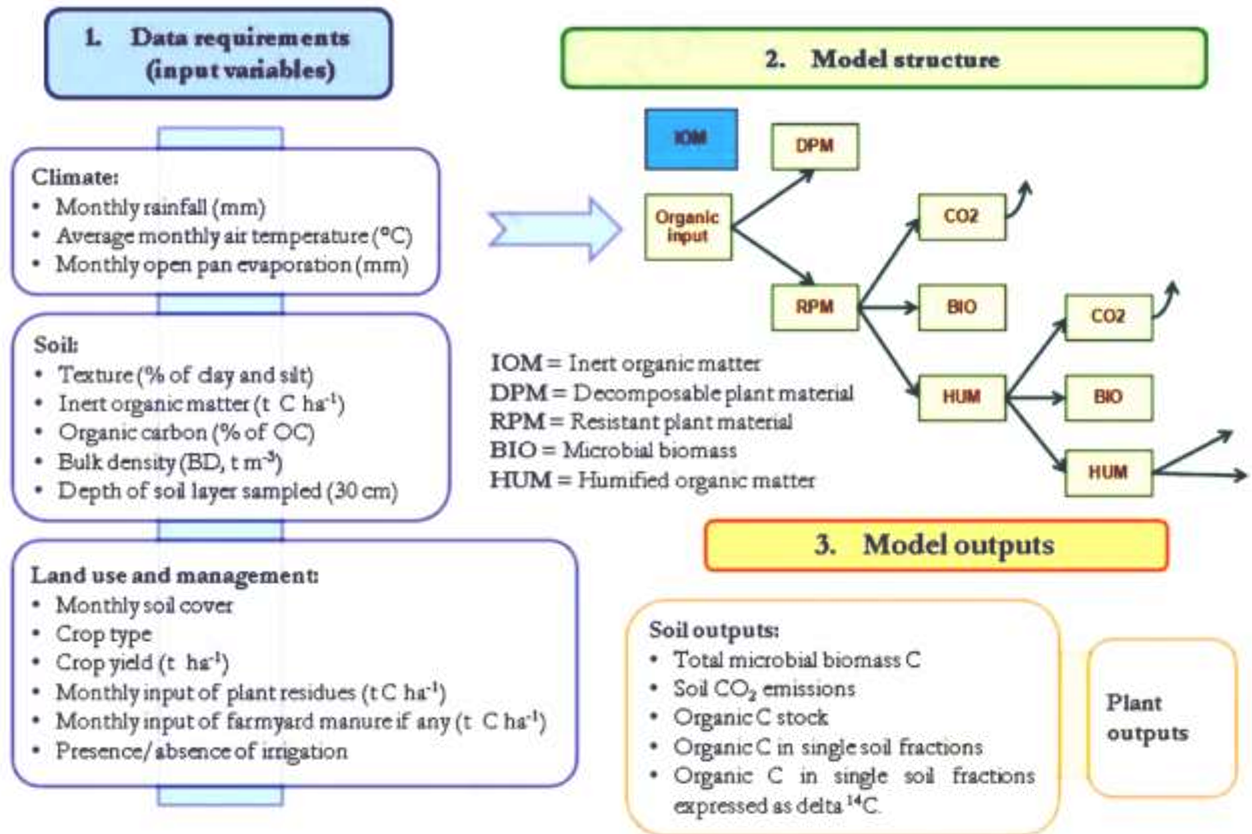
Predicting long-term Soil Organic Carbon sing Roth-C

The Rothamsted Carbon (Roth-C) Model (Coleman and Jenkinson, 1999), is one of the leading SOC turnover models and has been widely used in different environments, soil types and managements (e.g. Kamoni et al. 2007, Ludwig et al., 2005; Shirato et al., 2005; Zimmermann et al., 2007; Sitienei, 2017). It needs few, easily obtainable input parameters (Coleman and Jenkinson, 1999) and has the advantage of being testable with existing datasets (Shirato et al., 2005). Roth-C has hitherto been used and validated under Kenyan conditions based on long term field experiments at Kabete and Machanga field stations (Kamoni et al., 2007).

Model Structure and Data Requirements

Model Structure. The Roth-C is a process-based, multi-compartmental pure SOC decomposition model (Coleman & Jenkinson 1996) that simulates the effect of soil type, temperature, moisture content and plant cover on SOC turnover process. The SOC simulation rests on five conceptual pools (Figure 3) Incoming plant material is separated into decomposable plant material (DPM) and resistant plant material (RPM), which are decomposed to produce humified organic matter (HUM), microbial biomass (BIO) and evolved CO_2. Soil clay content determines the proportion of evolved CO_2 and BIO + HUM. The HUM and BIO pools undergo further decomposition. Each of these compartments decomposes by first-order kinetics with decay rate constants of 10, 0.3, 0.66 and 0.02 per year for DPM, RPM, BIO and HUM, respectively (Coleman and Jenkinson, 1999). The mode also includes an inert organic matter pool (IOM) which is resistant to decomposition.

Data requirements and sources. The model uses a monthly time step to calculate total SOC (t ha^{-1}), microbial biomass carbon (t ha^{-1}), D14C (from which the equivalent radiocarbon age of the soil can be calculated) and its different pools on years to centuries timescale (Jenkinson et al., 1987, 1992; Jenkinson and Coleman, 1994). The required input parameters include (i) Climate Data: monthly average air temperature(°C), monthly rainfall (mm) and monthly open-pan evaporation (mm). The climate data was obtained from Kabete field station on-site sub weather station; (ii) Soil data (values derived from actual field measurements): clay content (67 %), initial soil organic carbon (SOC) stock (43.13 t C ha^{-1}), depth of the soil layer, approximated at 30cm (Table 1). Inert organic carbon (IOM) (Mg ha^{-1}) was obtained following Falloon et al. (1998): IOM = 0.049 × TOC$^{1.139}$, where TOC is total organic carbon (Mg ha^{-1}); (iii) Land use and land management data: (a) soil cover (whether soil is covered by a crop or is fallow) was assumed to occur all year round (except for months 1, 2 and 8) owing to the cropping systems practiced (b); monthly input of plant residues (t C ha^{-1}) and monthly input of farmyard manure (FYM) (t C ha^{-1} year^{-1}).The monthly inputs were derived from an initial annual input (Table 2) and that acted as a starting point in model initialization. After model adjustment, the annual inputs were redistributed across the twelve months in a year; (c) residue quality factor (DPM/RPM ratio of 0.67 (also Kamoni et al., 2007) and the organic inputs were split into 49% DPM, 49% RPM and 2% HUM fixed on a default value setting for agricultural plant material and farmyard manure (Coleman and Jenkinson 1999).



SOURCE –Bene et al. (2016)

Figure 3. Data requirements and Structure of the Roth-C model.

Simulation procedure. For the Roth-C model to simulate and predict influence of organic inputs and cropping systems on SOC, the model was run to equilibrium in inverse mode. The plant C input was adjusted and then redistributed through the months, and the equilibrium run repeated iteratively until the modelled values of C at equilibrium matched the initial measured SOC stock. The model was initialized using the weather and soil conditions of Kabete field station for 10,000 years ending in 2015 for all treatments. Having determined the plant additions and carbon contents of the soil organic matter pools, specific management files were created_using the input data collected from the site for the respective treatments and the simulations were run, assuming constant C input over time and constant environmental conditions, from 1990 to 2020.

RESULTS AND DISCUSSION

Soil moisture as influenced by legume integration and fertilizer application

There was a significant ($P \leq 0.05$) increases in soil moisture content (%) in maize/dolichos intercrop with application of FYM+TSP+Urea and FYM as compared to dolichos-maize rotation and sole maize without fertilizer application in the LRS (Table 3).

Table 2. Plant C inputs used in the Roth-C model.

	C inputs (t C ha^{-1} year^{-1})			
Cropping System	Control + Residue	FYM (10tha^{-1}) + Residue	FYM (5tha^{-1}) + Urea + TSP (30kgha^{-1}) + Residue	Urea + TSP+ Residue (60kgha^{-1})
Crop rotation	2.1	2.43+2.23	1.215+1.12	2.4
Monocrop	2.05	2.25+2.23	1.125+1.12	2.2
Intercrop	2.15	2.55+2.23	1.275+1.12	2.55

Note: Residue was calculated from grain yield data using a harvest index (HI) and converted into t Cha^{-1}

Table 3. Effects of cropping systems and fertilizer application on soil moisture content (%).

Season	Treatment	Dolichos-Maize	Maize/dolichos	Maize	Mean
LRS	Control	24.877[ab]	25.745[abc]	23.483[a]	24.701[a]
	FYM	30.091[cd]	30.218[d]	29.778[cd]	30.033[c]
	TSP/FYM/Urea	29.922[cd]	30.385[d]	29.562[c]	29.961[bc]
	TSP/Urea	28.502[bcd]	28.167[bcd]	27.639[bcd]	28.101[b]
Mean		28.348[a]	28.629[a]	27.616[a]	
SRS	Control	22.354[a]	22.646[a]	23.106[a]	22.702[a]
	FYM	30.835[cd]	31.769[d]	31.329[d]	31.311[c]
	TSP/FYM/Urea	30.877[d]	30.999[d]	31.414[d]	31.103[c]
	TSP/Urea	27.816[bcd]	27.734[bcd]	29.435[cd]	28.332[b]
Mean		27.971[a]	28.287[a]	28.821[a]	

LSD: Cropping system*Treatment = 2.63; Season* Cropping system*Treatment = 3.72. Within rows means followed by the same letters are not significantly different at P = 0.05 according to Fisher's Protected Least Significant Difference Test.

Higher moisture content was obtained in maize/dolichos following FYM application of which was not significantly ($P \leq 0.05$) different from dolichos-maize with FYM+TSP+Urea application in the SRS and LRS. Sole maize had significantly ($P \leq 0.05$) low moisture content across fertilizer inputs and seasons (Table 3). The increased soil moisture content with application of FYM and combined FYM+TSP+Urea in the intercropping system is attributable to improved ground cover and increased amount of organic matter that resulted into improved soil structure and reduced water losses through soil erosion, and reduced evapotranspiration. Wortman *et al.* (2012) and Smith et al. (2016) reported increased soil moisture under legume systems in subsequent seasons and attributed the high soil moisture to improved soil physical properties such as improved water retention, good water holding capacity, increase in porosity and aggregate stability resulting in better soil moisture retention. This is also in agreement with Boateng *et al.* (2006) and Adeleye *et al.* (2010) who found out that higher rates of FYM increased soil water retention. The enhanced soil moisture with integration of dolichos as an intercrop could also be as a result of dense ground cover leading to reduced evaporation from the soil surface. This observation agrees with Chepkemoi *et al. (*2014) who reported improved soil moisture in intercropping systems compared with sole cropping and attributed the same to increased shading hence reducing water loss through evaporation. There was reduced soil moisture in dolichos-maize rotation with TSP+FYM+Urea and TSP +Urea application in the SRS and LRS as compared to sole-maize. This was possibly caused by the dolichos in rotation utilizing moisture for development hence depleting the soil profile of moisture. Hoyt and Leich (1983) observed lower soil moisture in plots following legumes and ascribed the decrease to moisture depletion by legumes. Another reason could have been that dolichos developed ground cover more rapidly but maintained it for a shorter time hence protecting the soil least at harvest (Sitienei et al 2017; Mureithi et al., 2003). The increase in soil moisture in the subsequent season was mainly because of increased amount of received rainfall (Figure 1). Namoi et al., 2014; Muli et al. (2015) reported that soil moisture is primarily determined by amount and intensity of received rainfall. This could also be explained in terms of increase in organic matter buildup, improved soil structure and tilth and water retention following FYM application. This finding agrees with those of Wang *et al.* (2012) and Cercioglu (2017) who found organic manure application to significantly ($p>0{\cdot}05$) increased total porosity, field capacity and water retentions.

Soil organic carbon as influenced by legume integration and fertilizer application

Significantly ($P \leq 0.05$) high soil organic carbon (SOC) content (%) was obtained in dolichos/maize intercropping system with application of FYM and FYM+TSP+Urea across seasons (Table 4). However, the SOC content with application of FYM alone was not significantly different from that of combined application of FYM+TSP+Urea across dolichos/maize intercrop, dolichos-maize rotation and sole maize cropping systems (Table 4).

The SOC (%) was higher in dolichos/maize intercrop with FYM and TSP+FYM+Urea application although not significantly different from dolichos-maize and sole maize in the SRS (Table 4). The high soil organic carbon obtained with integration of dolichos and application of FYM and TSP+FYM+Urea in the SRS can be attributed to direct C input from manure and indirect C input through increased net primary production through crop residue incorporation, which led to gradual buildup of SOC over time. These findings agree with those of Whalen and Chang, (2002); Bhattacharyya et al. (2010) who reported high soil organic carbon levels in combined manure and legume integration treatments.

Table 4. Effects of cropping systems and fertilizer application on soil organic carbon (%).

Season	Treatment		Dolichos-Maize	Maize/dolichos	Maize	Mean
LRS	Control	Control	1.961[a]	1.963[a]	1.925[a]	1.949[a]
	FYM	FYM	2.405[efg]	2.487[gh]	2.318[def]	2.403[de]
	TSP/FYM/Urea	TSP/FYM/Urea	2.341[def]	2.414[efgh]	2.284[cde]	2.346[d]
	TSP/Urea	TSP/Urea	2.158[bc]	2.221[cd]	2.149[bc]	2.176[b]
Mean			2.216[ab]	2.271[bc]	2.169[a]	
SRS	Control		2.032[ab]	2.006[a]	2.004[a]	2.014[a]
	FYM	FYM	2.493[gh]	2.555[h]	2.449[fgh]	2.499[f]
	TSP/FYM/Urea	TSP/FYM/Urea	2.449[fgh]	2.509[gh]	2.420[efgh]	2.459[ef]
	TSP/Urea	TSP/Urea	2.241[cd]	2.284[cde]	2.221[cd]	2.249[c]
Mean			2.304[c]	2.338[c]	2.273[bc]	

LSD: Cropping system*Treatment = 0.02 Season* Cropping system*Treatment = 0.13.

Within rows means followed by the same letters are not significantly different at P = 0.05 according to Fisher's Protected Least Significant Difference Test.

Higher SOC realized with application of FYM is similarly attributable to its slower decomposition rate and hence gradual SOC build up. Ghimire *et al.* (2012) had likewise observed a buildup of soil organic carbon levels with organic fertilizer addition and incorporation of residues over time.

There were no significant increases in SOC levels across dolichos/maize intercrop, dolichos-maize rotation and sole maize with FYM and TSP+FYM+Urea application across seasons. The slow buildup of organic carbon in soil can partly explain lack of significant differences in both seasons. According to Baldock (2009), changes in soil organic carbon are slow and can take up to five years. Kouyate *et al.* (2012); Myaka *et al.* (2006), correspondingly reported that integration of legumes within cropping systems did not improve SOC in the short-term. The significant increase of SOC observed in dolichos/maize intercrop with TSP+FYM+Urea application can be explained in terms of readily available nutrients supplied by inorganic fertilizers and better moisture retention because of FYM application leading to increased crop biomass production and hence leaf senesce thereby contributing to enhanced soil organic matter. This agrees with Goyal et al. (1992) who found that combined fertilizer application resulted to improved SOC contents and linked the same to increased root growth associated with greater organic matter inputs. Similarly, studies that compared above versus belowground C input to soil generally found a greater stabilization of root-derived C than crop residue-derived C (Denef and Six 2006; Gale and Cambardella 2000). Additionally, higher organic C under dolichos/maize intercrop could be credited to its higher biomass production offering less competition to the companion crop. This may have, as well, allowed the companion crop to develop more biomass. Cheruiyot *et al.* (2001), also observed greater increases in biomass production in maize following dolichos compared to other legumes.

Soil carbon stocks as influenced by legume integration and fertilizer application

Significantly ($P \leq 0.05$) high SOC stocks (t C ha^{-1}) were obtained in maize/dolichos intercrop with FYM application compared to sole maize and dolichos-maize rotation during LRS. However, there were no significant differences in maize/dolichos intercrop with TSP+FYM+Urea application (Table 5). The same trend was observed during the SRS in intercrop with FYM and TSP+FYM+Urea.

Application of FYM and TSP+FYM+Urea increased SOC stocks across all cropping systems in both seasons. This is because, FYM application directly added C input into the soil thus enhancing soil physical conditions such as improved soil structure for better retention and uptake of water, and nutrients in soil. The combined fertilizer application (TSP+FYM+Urea) similarly led to an increase in SOC stocks because of greater C input associated with enhanced primary production and crop residues retention and eventual decomposition in soil. According to Bhattacharyya et al. (2000), addition of inorganic fertilizers alone increases TOC marginally while introduction of manure brought an increase in TOC. Additionally, increased SOC might lead to a positive feedback on plant growth and thus increase the C input of the main crop (Brock et al., 2011; Poeplau and Don 2015). The observed increase in this study may however be short-lived as attested by Kapkiyai (1999), who noted a decline in SOM even when manure was applied, and maize residue retained in a long-term study in Kenya. Woomer et al. (1997), estimated that to maintain organic carbon stock in the soil, 35 t/ha of manure or 17 t/ha manure with 16 t/ha of stover would be required annually over a period of time.

Table 5. Calculated SOC stocks (t C ha^{-1}) under maize-based systems.

Cropping System	Treatment	LRS	SRS
Crop Rotation	Control	43.13[a]	44.70[abc]
	FYM	52.91[efg]	54.84[fg]
	TSP/FYM/Urea	51.49[defg]	53.88[efg]
	TSP/Urea	47.48[abcd]	49.30[cde]
Intercropping	Control	43.19[a]	44.14[ab]
	FYM	54.71[fg]	56.20[g]
	TSP/FYM/Urea	53.11[efg]	55.19[fg]
	TSP/Urea	48.85[bcde]	50.26[def]
Sole maize	Control	42.34[a]	44.08[ab]
	FYM	50.99[def]	53.87[efg]
	TSP/FYM/Urea	50.25[def]	53.23[efg]
	TSP/Urea	47.28[abcd]	48.85[bcde]

Key: Means in a column followed by the same letter(s) are not significantly different at $P = 0.05$ according to Fisher's Protected Least Significant Difference Test.

Modelling influence of legume integration and fertilizer application on SOC dynamics over a 20-year period

Sole maize

The projected SOC stocks in sole maize cropping system with application of FYM maintained relatively high carbon stocks over a 20-year period compared to application of TSP+FYM+Urea and TSP+Urea. The TSP+Urea and control treatment had the lowest carbon stocks (Figure 4).

The high levels of SOC stocks with application of FYM and TSP+FYM+Urea compared to TSP+Urea and control, over the 20-year period, could be explained in terms of accumulated residue effect of the FYM and more direct carbon additions through the incorporated maize stover in soil. Cereals, particularly maize have been reported to return nearly twice as much residue to the soil compared with, for instance, legumes consequently resulting to higher levels of SOM increase (Reicosky, 1995). Curtin et al. (2000), reported that a wheat crop would add between 4.2 and 5.4 t Cha^{-1} annually. Similarly, in Argentina maize with 3 t Cha^{-1} of residue was found to significantly reduced soil carbon loss from the system (Studdert and Echeverria, 2000).

Projected low levels of SOC in control and TSP+Urea treatments are due to lack of direct organic inputs and slow pace of organic matter production upon incorporation of the crop residues after harvest. Bhattacharyya et al. (2000), reported that addition of inorganic fertilizers alone could only increase TOC marginally while introduction of manure enhanced TOC levels. In other studies, Fontaine et al. (2004), demonstrated that long-term mineral fertilizer (NPK) application led to a decrease of soil organic carbon due to higher mineralization rate. Yang et al. (2003); Chen et al. (2010) showed that the system of management (e.g. tillage systems, which depends only on NPK fertilizer application) without incorporation of plant residues back to the soil, or without application of organic manures, cannot resist the SOC depletion effectively. In contrast, the application of mineral fertilizers incorporated with organic manures increases the SOC content. This, however, is likely to be the case after some time as depicted by the fitted logarithmic trendline (Figure 4). Singh et al. (2004) had earlier reported that organic carbon content in the surface soils significantly increases with repeated additions of farm yard manure/poultry manure/urban compost along with 50% NPK and 5 t $FYMha^{-1}$ to soybean and 100% NPK to wheat, and modelled TOC values followed this trend.

Dolichos-maize rotation and intercropping

The projected carbon stock levels, over a 20-year period, were significantly high across treatments, compared to sole maize, for the two cropping systems. The intercrop had slightly higher levels of SOC across treatments although not significantly different from the rotation system (Figure 5 and Figure 6). Increase in projected SOC stocks with legume integration could be attributed to enhanced nutrient availability, through BNF, and hence enhanced crop growth and high biomass production. With increased biomass, more C was added into the soil. There was a significant increase in soil organic carbon stocks in FYM treatment followed by TSP+FYM+Urea treatments compared to TSP+Urea and Control treatment which had the lowest level of SOC stocks estimated over time (Figure 4 and Figure 5) for both cropping systems.

The enhanced SOC with FYM and TSP+FYM+Urea application in both cropping systems over the 20-year period may partly be explained by the fact that FYM decomposes slowly and directly adds soil C thereby enhancing the levels of soil organic carbon over time.

Feng and Li (2001); Vanlauwe, 2017 also reported that manure was more resistant to microbial decomposition than crop residues and, consequently, for the same carbon input, carbon storage is higher with manure application than with plant residues. Yokozawa et al. (2010), who used Roth-C to simulate soil C stocks in Japanese paddy and upland fields at a national scale, showed that farmyard manure application to paddy fields (1.0 Mg C ha^{-1} yr^{-1}) and upland fields (1.5 Mg C ha^{-1} yr^{-1}) over a 25-year period increased soil stocks by 0.30 Mg C ha^{-1} yr^{-1}, indicating that farmyard manure application contributed 25% of the increase in soil C stocks.

Similarly, addition of TSP and Urea contributed to increased crop growth with resultant effect of pronounced accumulation of soil organic matter through increased litter production at surface layer although not to the same level as projected for FYM application alone and/or in combination with TSP+Urea. According to Menšík (2018), the application of mineral fertilizers incorporated with organic manures increases the SOC content. The lower SOC in FYM+TSP+Urea compared to FYM alone, can be argued against the background of readily available nitrogen source (Urea) for microorganisms and hence accelerated decomposition of FYM and crop residue thus contributing to losses of C as carbon dioxide with a small fraction being sequestered. This observation agrees with that of Kapkiyai *et al.* (1999); Fornara and Tilman (2012), and Wells et al. (2017) who reported higher organic matter decomposition rates achieved through application of combinations of inputs.

Overall, the projected SOC stocks showed a steady increase (Figures 5 and 6) in soil organic carbon over the twenty-year period. This is however contrary to the findings of other researchers who had reported a decrease in SOC with application of mineral fertilizers (e.g. Mensik et al. 2018; Yang et al., 2012; Chen et al., 2010; Kipkai, 1999). They demonstrated that long-term mineral fertilizer (NPK) application led to a decrease of soil organic carbon due to higher mineralization rate. This argument was similarly confirmed when an a logarithmic trendline (Figures 5 and 6) was fitted to data. The logarithmic trendlines (with a good fit as R squared was closer to 1) tended to suggest a rapid and steep rise in stored soil organic carbon across cropping systems and treatments in the first 7 years but increase became less steep

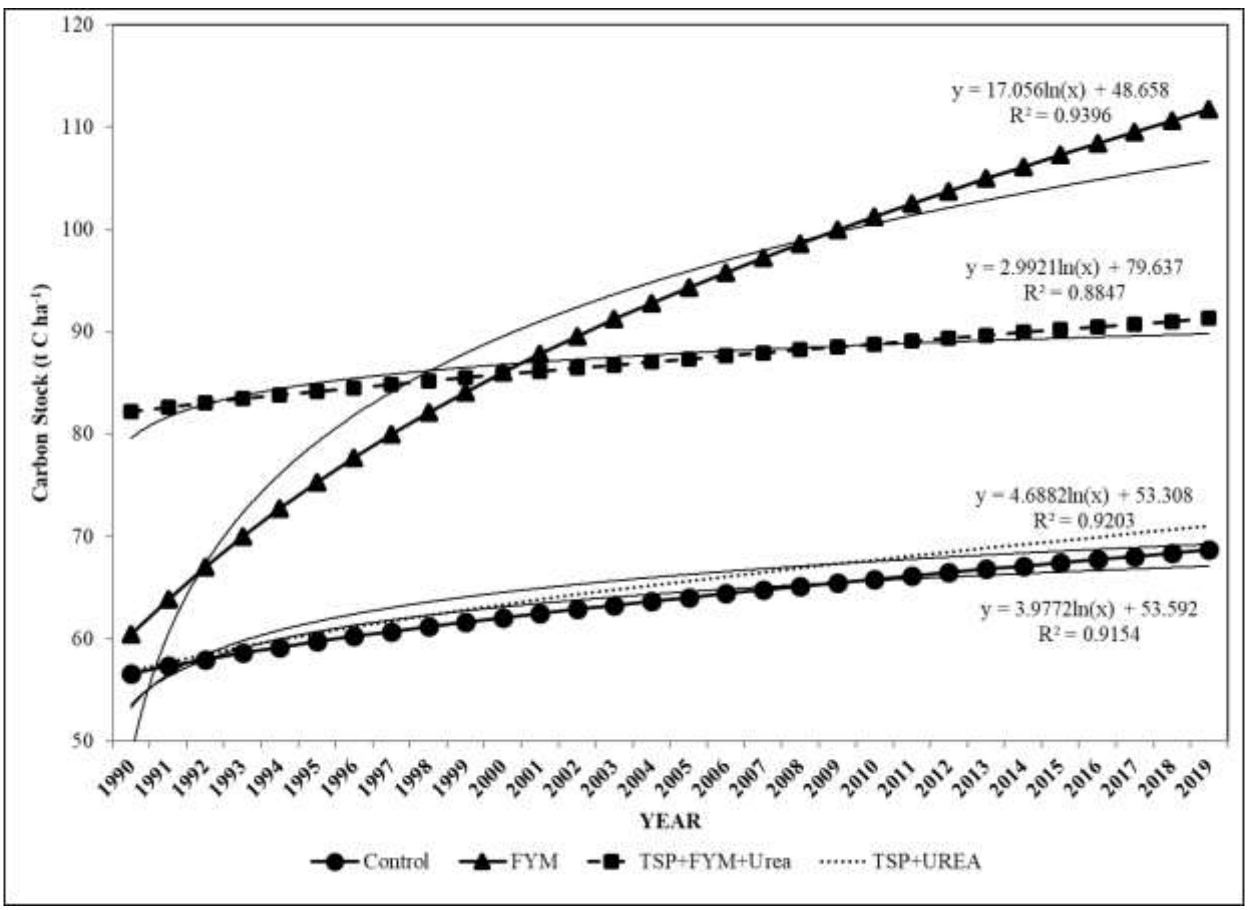


Figure 4: Soil organic carbon stock dynamics over a 20-year period under sole maize with fertilizer application (Continuous solid line indicates logarithmic trendline).

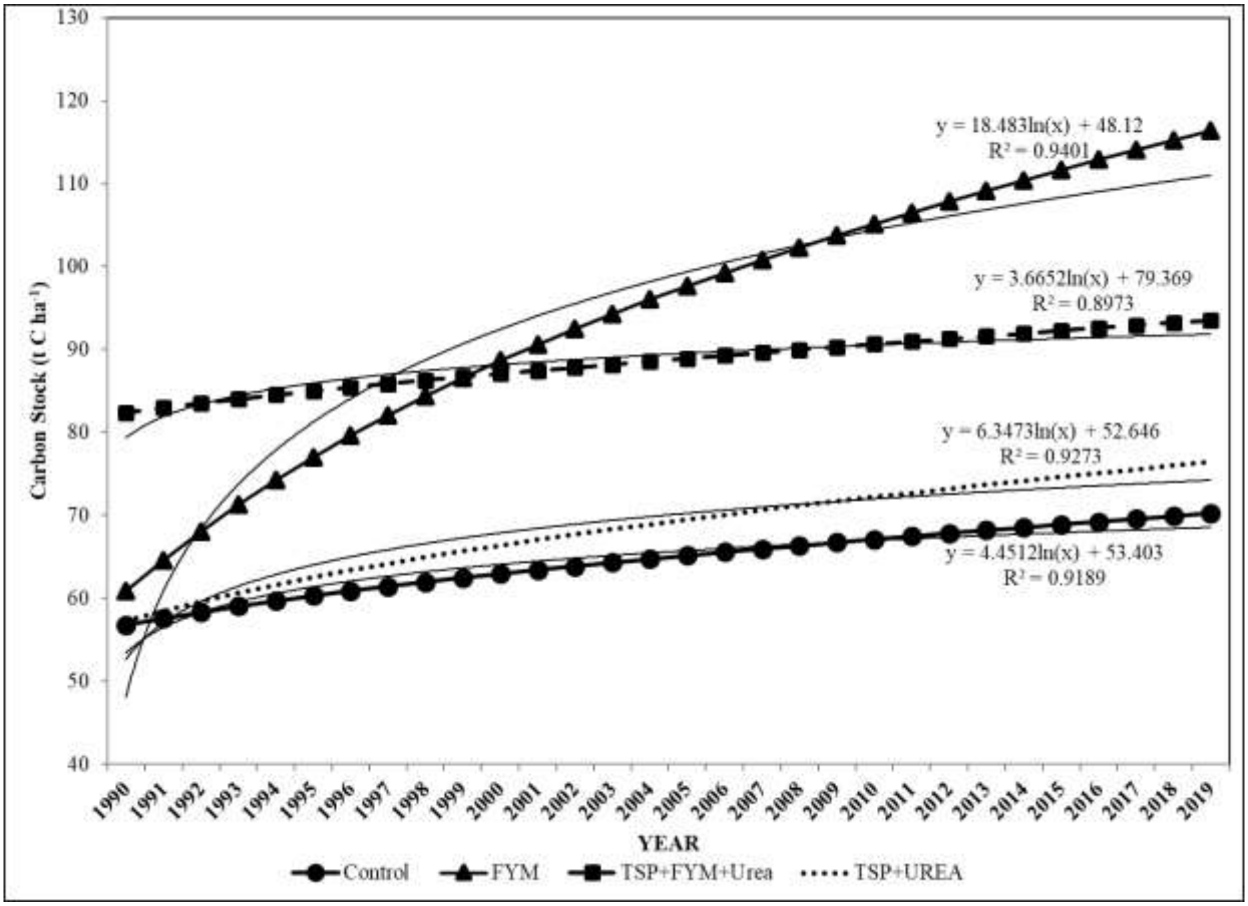


Figure 5: Soil organic carbon stock over a 20-year period under dolichos-maize rotation with fertilizer application (Continuous solid line indicates logarithmic trendline).

up to the year 2009/2010 when the accumulated SOC started to steadily decline. This is an indication that it will tend to level off at some point. In this regard, Sommer and Bossio (2014) argued that an increase in SOC does not proceed linearly for many years, but SOC sequestration, for instance, in upland soils usually levels off at some point in time, e.g. after 20–30 years (West and Six, 2007). In some long-term experiments no further increase in SOC stocks were observed despite higher C-inputs (Chung et al., 2010; Gulde et al., 2008; Paustian et al., 1997) and this may be explained by the theory of C-saturation of the whole soil or some fractions (Stewart et al., 2007). Thus, estimates based on a few years may not represent longer-term underlying trends (Lokupitiya et al., 2010; Paustian et al 2017).

CONCLUSION

The current study investigated the effect of dolichos integration and combined application of fertilizers on soil moisture, soil carbon stocks and carbon stock changes over a 20-year period in maize systems of Kabete sub-County, Kenya during the long andshort rains of 2015/2016. The highest levels of soil moisture, soil organic carbon and soil organic carbon stocks were observed across the seasons in maize/dolichos intercrop with application of FYM and FYM+TSP+Urea. Over a 20-year period, SOC stocks maintained a significant increase with application of TSP+FYM+Urea and FYM in the order; maize/dolichos intercrop, rotation and sole maize system. The control and TSP+FYM treatments had the least SOC stocks across the cropping systems with no significant difference in SOC observed between them although TSP+Urea had pronounced SOC values. This meant that FYM was the primary contributor to the SOC pool compared to chemical fertilizers. The use of organic fertilizer (FYM) therefore directly increased SOC contributing to increased carbon sequestration. The projected SOC results over a 20-year period also confirmed similar trends. The RothC model demonstrated that over the 20-year period, addition of FYM alone and/or in combination with organic fertilizers substantially enhanced the levels of SOC across the cropping systems. To enhance soil carbon storage, dolichos/maize intercrop alongside application of FYM and combined FYM TSP+Urea is therefore the best bet technological package for increased productivity and sustainability of the smallholder farming systems of Kabete, Nairobi County.

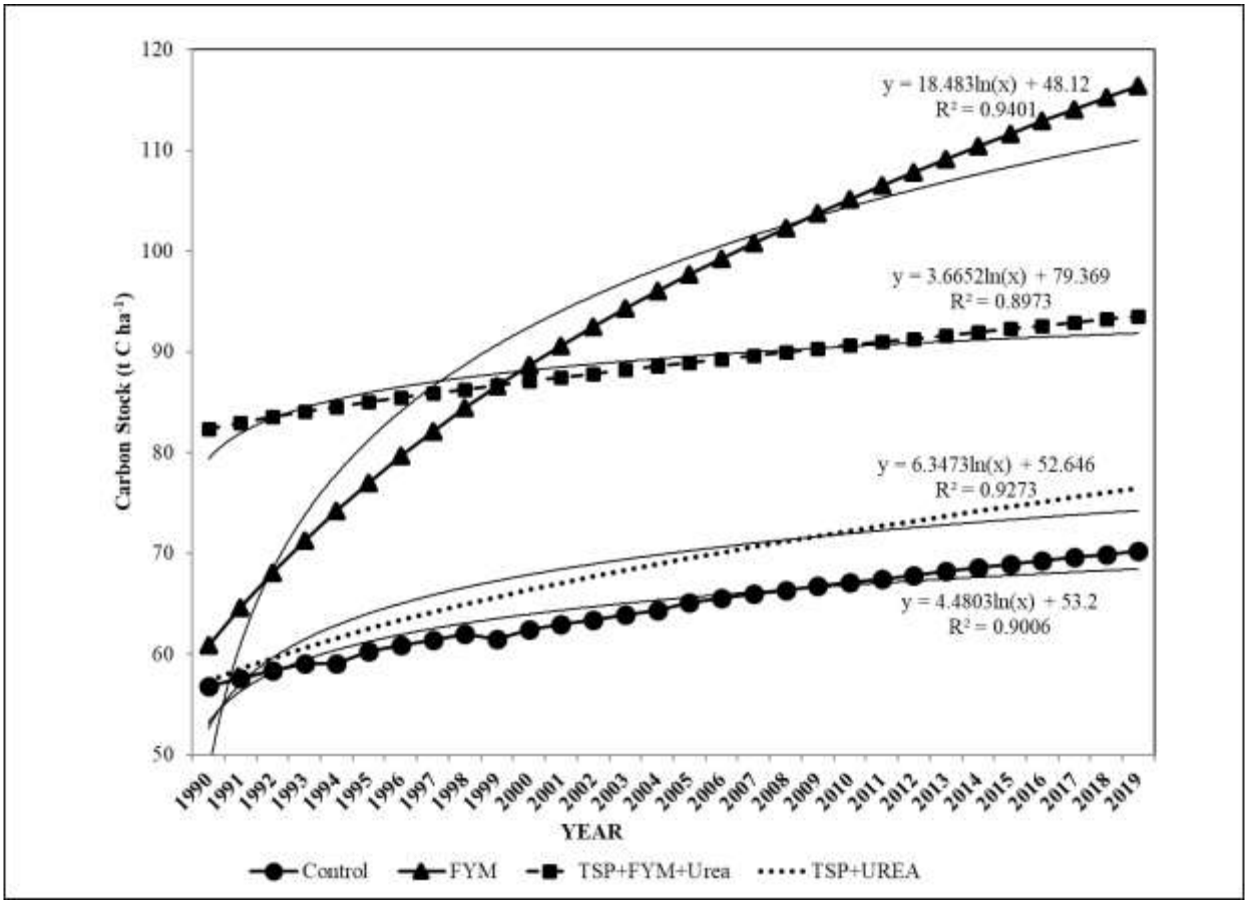


Figure 6: Soil organic carbon over a 20-year period under dolichos/maize intercrop with fertilizer application (Continuous solid line indicates logarithmic trendline)

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Conflict of interest. The authors hereby declare that they have no conflict of interest.

Compliance with ethical standards. The study did not involve human subjects and therefore no consewnt was required and/or authorization by an ethical or bioethical committee or equivalent declaration.

Data availability. The data is available with the second author - Ruth C. Sitienei, ruthsity@gmail.com upon reasonable request.

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