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Soil organic carbon stocks under coffee agroforestry systems and coffee monoculture in Uganda

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ABSTRACT

Coffee agroforestry systems (CAS) are considered as a climate change mitigation option through carbon sequestration. However, most studies on CAS have concentrated on management and productivity of the coffee plants with little known about the soil organic carbon (SOC) stocks. We conducted a study to quantify and compare the SOC stocks among *Coffea arabica* L. (Arabica coffee), *Coffee canephora* Pierre ex Froehn (Robusta coffee) agroforestry systems and Coffee monoculture (coffee monocrops) in Uganda. Soil samples were collected at 0–15 cm and 15–30 cm and tested using routine soil testing procedures. We found that there was higher SOC under CAS than coffee monocrops. When intercropped with non- fruit tree species, Robusta CAS produced higher SOC (57.564 tC/ha) compared to the Arabica CAS (54.543 tC/ha). In contrast, Arabica CAS stored more SOC (54.01 tC/ha) compared to Robusta CAS (49.635 tC/Kg) when intercropped with fruit trees like *Artocarpus heterophyllus* Lam. and *Mangifera indica* L. Under the coffee monocrop systems, Robusta coffee sequestered 4.86 tC/ha more SOC than Arabica coffee. The study showed that a farmer growing Robusta coffee intercropped with non-fruit trees is likely to benefit more from soil carbon credits than a farmer growing Arabica coffee with the same trees. Farmers growing Arabica coffee would sequester more carbon if intercropped with fruit trees. There is need for policy incentives that encourage the planting and maintenance of shade trees in coffee plantations for the benefit of carbon sequestration.

1. Introduction

Exploring relatively low cost approaches to carbon sequestration is one of the global environmental policy goals to address climate change (Montagnini and Nair, 2004). Agroforestry is one of the approaches that are currently being promoted to address climate change through carbon conservation in the woody component and soil (Nair, 2012; Nair et al., 2009a). It is recognised as a greenhouse gas- mitigation option under the Kyoto Protocol (Nair et al., 2009a). It is also considered as an option aimed at reducing emission of greenhouse gases in the United Nations based REDD+ (reducing emissions from deforestation and forest degradation, conserving and enhancing forest carbon stocks, and sustainably managing forests) program for tropical developing regions (Atangana et al., 2014). Agroforestry is a suitable option for carbon sequestration because under this land use system most of the land remains available for production of other crops (Schoeneberger, 2009) and this is important for food security and enhancing household incomes (Pandey, 2002).

Despite studies showing the potential of agroforestry in sequestering Carbon (Albrecht and Kandji, 2003; Pandey, 2002), estimates of the amount of Carbon sequestered under specific agroforestry systems are scarce due to variability of soil, resource constraints and complexity of agroforestry systems (Tumwebaze et al., 2011; Nair et al., 2009b). The understanding of soil organic carbon dynamics under different agroforestry systems is not adequate (Nair et al., 2009b). Most studies have concentrated on above ground biomass and carbon in agroforestry systems (Segura et al., 2006). This scenario makes it difficult to promote agroforestry systems in voluntary and non-voluntary carbon credit schemes that use financial incentives to reduce emission of greenhouse gases (Atangana et al., 2014).

The objective of this study was to quantify and compare soil organic carbon (SOC) stocks in *Coffea arabica* L. (Arabica coffee) and *Coffee canephora* Pierre ex Froehn (Robusta coffee) agroforestry systems in Uganda. These two types of coffee species account for about 99% of the world coffee bean production

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(DaMatta and Ramalho, 2006). Robusta coffee is indigenous in Uganda and grown in the low altitude areas (1200 m.a.s.l) while Arabica coffee was introduced into Uganda from Ethiopia and Malawi in 1900 and is grown in highland areas of about 1500–2300 m.a.s.l (UCDA, 2007). Coffee is Uganda's major cash crop and the country's largest agricultural foreign revenue earner with about 1.32 million households directly involved in its production (Van Asten et al., 2011; UBOS, 2011). It is commonly grown with shade trees such as *Ficus natalensis* Hochst., *Mangifera indica* L. and other species that have socio-economic and ecological value to farmers (Munyuli, 2011). However there are other farmers who prefer coffee monocultures while others grow coffee with Bananas (Oduol and Aluma, 1990). Coffee is mainly grown by Smallholder farmers whose average farm sizes range from 0.5 to 2.5 ha and total area under coffee production in Uganda can be estimated at 272,000 ha (UBOS, 2011). We envisage that this study will create avenues for exploiting the potential for carbon sequestration in coffee agroforestry systems and may be a basis for exploring carbon credit incentives for millions of farmers involved in coffee farming.

2. Methodology

2.1. Study area

The study was conducted in four districts in Uganda i.e. Kasese, Kabarole, Bushenyi and Ibanda (Fig. 1), that were purposively selected depending on the type of coffee grown. Kasese and Kabarole districts were selected to represent Arabica coffee growing areas and Bushenyi and Ibanda to represent Robusta coffee growing areas respectively. Kasese lies between latitudes

0° 11′11.36″N and longitude 30°05′17.12″E while Kabarole is located at 0° 35′05.15″N latitude and 30°15′06.76″E longitude. Bushenyi lies at 0°32′30.00″S latitude and 30°11′06.00″E longitude while Ibanda is located at 0^0 05′47.48″S latitude and 30°34′26.63″E longitude.

2.2. Soils and climate

The Arabica coffee growing district of Kabarole consists of Ferralsols which are mainly sandy clay loam with mean annual

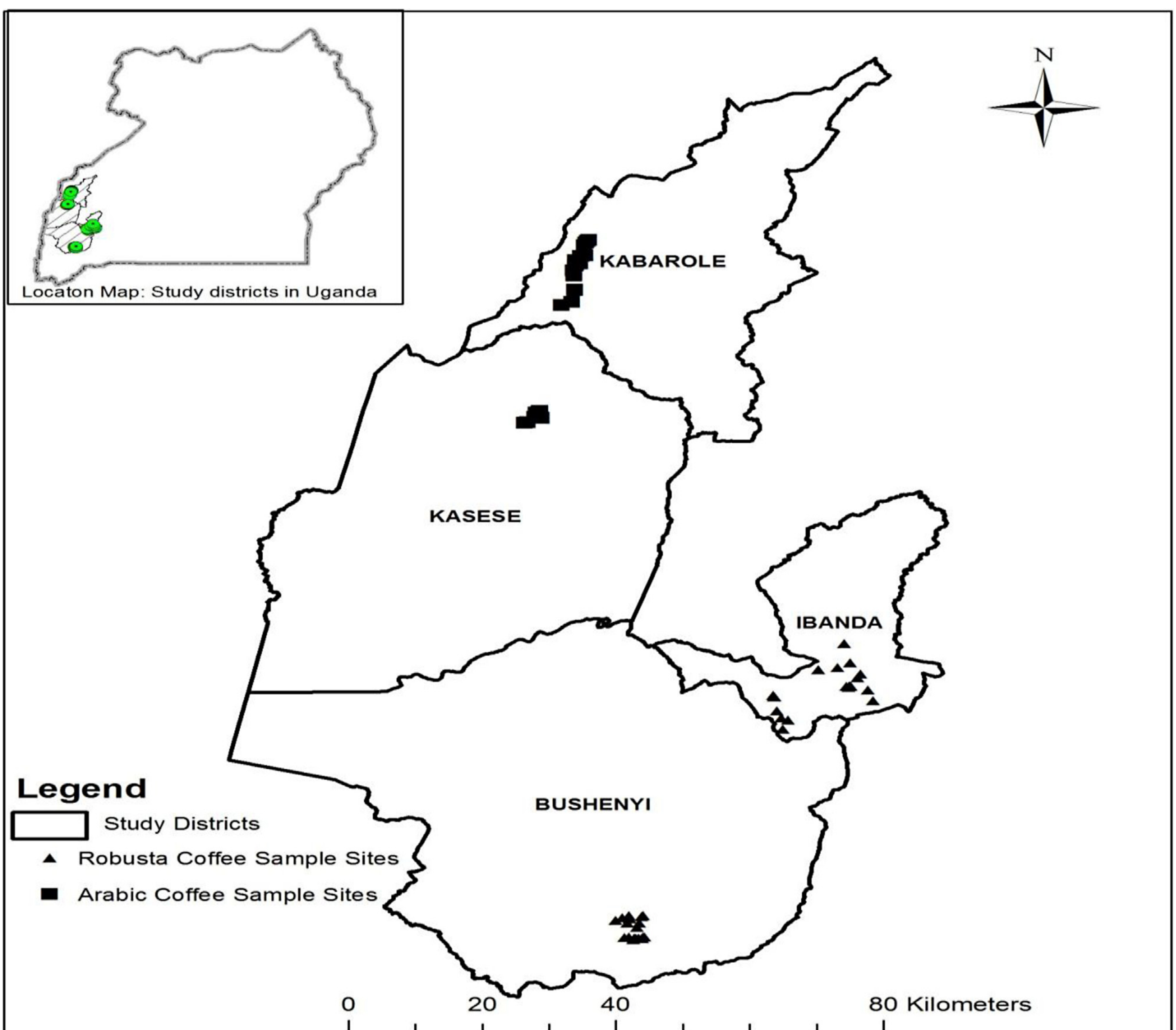


Fig. 1. Map of Uganda showing the sampling sites.

rainfall range of 750–1000 mm and average temperature of 19 °C, while Kasese district consists of humic high altitude, organic soils that are non-hormorphic, some parts consist of alluvial deposits and other have volcanic ash (Panagos et al., 2011) with mean annual rainfall range of 912.2–1287 mm and temperature range of 16.3–29.9 °C.

The Robusta coffee growing districts of Bushenyi and Ibanda consist of Ferrallitic soils with dark horizons and mainly sand clay loam soils (Panagos et al., 2011), with mean annual rainfall range of 750–1000 mm and temperature range of 16.4–29.1 °C.

2.3. Experimental design and data collection

A complete randomized design with a $(4 \times 2 \times 2)$ factorial treatment structure where factors included four levels of types of trees present on farm; two levels of coffee type and two soil depths was applied in the current study. Lists of coffee producers within each coffee region were obtained from Uganda Coffee Development Authority (UCDA) from which farmers where the study was conducted were selected. Based on farmers with the similar tree coffee combinations, 40 coffee producers with coffee farms ($\geq$0.5 ha) were randomly selected from each of two regions that grow Arabic and Robusta coffee respectively, for soil sampling. For any randomly selected farm, location of the farm was documented using a hand GPS, and information on age and spacing of the coffee plants and owner of the farm were recorded and existing shades trees identified using a para-taxonomists and later confirmed at Makerere University Herbarium. The selected farms that had coffee agroforestry systems consisted of either Robusta or Arabica coffee, intercropped with either fruit trees, such as *Artocarpus heterophyllus* Lam. *Persea americana* Mill. and *M. indica* L., or non-fruit trees, such as *Maesopsis eminii* Engl., *F. natalensis* Hochst. *Markhamia lutea* K. Schum., *Grevillea robusta* A. Cunn., *Erythrina abyssinica* Lam., *Senna spectabilis* (DC.) H.S. Irwin and Barneby, *Albizia* chinensis Merr., *Albizia coriaria* Welw. and *Ficus ovata* Vahl. Farms without trees consisted of coffee as a monocrop.

A grid of 2.5 m × 2.5 m was superimposed on 80 coffee agroforestry farms and five plots were randomly selected from each resulting into 400 plots in both coffee regions. The soil samples were collected using a soil auger with 0.083 m diameter at two depths; 0–15 cm and 15–30 cm. Three soil cores within each plot were bulked by depth to obtain a representative sample for the plot. After collection, soil samples weighing 1.5 kg were transported to the laboratory, air dried and run through a 2 mm sieve to remove stones and root fragments. The soil carbon concentrations were analyzed by the Walkley-Black method (Schnitzer, 1982) and Nitrogen by Kjedahl procedures (Elliott et al., 1999). Available Potassium was measured using flame photometer, phosphorous using extraction (Mehlich-3 solution) and calorimetric procedures and pH by a pH meter using 1:2.5 soil water extract (Okalebo et al., 2002). Bulk density was determined by collecting eighty samples of undisturbed soil from the study sites at two different soil depths using a core sampler.

The samples were weighed to obtain the wet weight and later oven dried at a temperature of 105 °C for two days to constant weight. Bulk density was calculated using the volume of the inner core sampler and the oven dry weight of the soil (Oelbermann and Voroney, 2007). All soil analysis was done at the National Agricultural Research Laboratories, Kawanda, Uganda.

2.4. Statistical analysis

The data were analysed using exploratory statistics (i.e., line graphs, bar graphs, and summary statistics) to assess the differences and the trends in SOC among the two coffee species. The SOC that were collected at two depths on the same plot were expected to be correlated, hence resulting into a repeated measure (Schabenberger and Pierce, 2002). Mixed model with repeated measurements was used to account for the correlation between depths; assess whether there were differences in SOC stored under the two coffee species and also assess whether the incorporation of trees in coffee farms stored more organic carbon than monoculture farms. The random factors included the farmers and the fixed effects included the type of coffee, type of trees present on farm and soil depths. Under the mixed model the autoregressive covariance structure was used since the data were equally spaced (Littell et al., 1996) in terms of depth. Soil bulk density data were analysed using the descriptive statistics and mixed model analysis, specifying autoregressive covariance structure. Before specifying the autoregressive covariance structure, and to account for the correlation due to repeated measurements in space (depth), different covariance structures [Compound symmetry (CS), 1st order autoregressive (AR (1)), and unstructured (UN)], were fitted to SOC data. Covariance structures were assessed using Akaike's Information Criterion (AIC) and Schwarz Bayesian Information Criterion (BIC). The covariance structures with small AIC and BIC was selected which is 1st order autoregressive (AR (1))

3. Results

Most farms in the Robusta coffee growing areas had sand clay loam soils (80% in Bushenyi and 44% in Ibanda) and the other farms either had clay or sandy clay soils. Most of the soils in Arabica coffee growing areas (Kabarole and Kasese) were sandy clay loam, sandy loam and clay loam. The mean pH in Arabica and Robusta coffee growing areas were 6.18 and 5.31, respectively. Farms with non-fruit trees and Robusta coffee had relatively higher soil organic carbon compared to the similar farms with Arabica coffee. Farms that did not have any trees had relatively low soil organic carbon compared to those with some trees irrespective of the type of coffee grown. The farms with a mixture of fruit and non-fruit trees had relatively higher soil organic carbon under Arabica coffee than other land management practices (Table 1).

Overall results indicate that soil organic carbon was significantly positively correlated ($r = 0.885$, $P = 0.000$) with nitrogen and weakly correlated with pH ($r = -0.036$) and phosphorus ($r = 0.134$).

Table 1
Soil organic carbon tC/ha under different coffee systems.

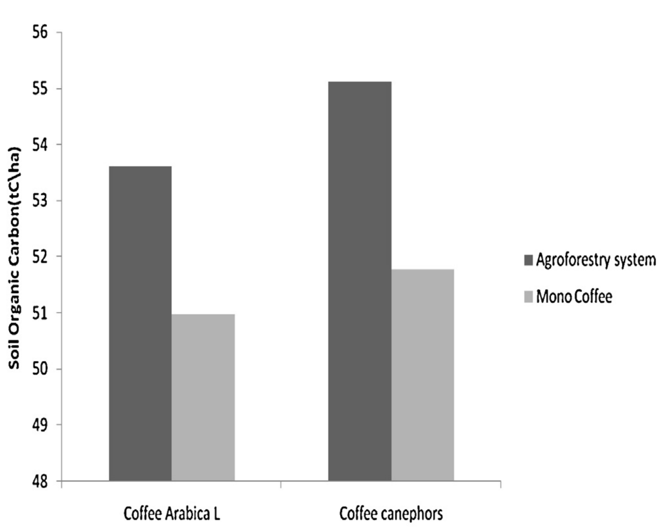
Type of coffee	Land management practice	Mean SOC (tC/ha)	Standard error
Arabica	Land planted with fruit trees	54.010	2.352
	Land planted with Non fruit and fruit trees	54.543	1.717
	Land devoid of any trees except coffee	50.987	2.103
	Land planted with Non fruit trees	51.170	2.514
Robusta	Land planted with fruit trees	49.635	1.568
	Land planted with Non fruit and fruit trees	57.564	1.778
	Land devoid of any trees except coffee	51.780	3.326
	Land planted with Non fruit trees	71.168	3.326

Nitrogen content in the soil was significantly highly positively correlated with Organic matter(r = 0.989, P = 0.000). Bulk density was negatively correlated with pH (r = −0.459), Nitrogen (r = −0.137) and Phosphorus (r = −0.447).

There was a significant difference in the bulk density (P = 0.001) among the farms depending on the type of trees on the land. Farms under coffee monocrop had least bulk density (1.162 Mg/m^3) compared to farms with coffee and tree agroforestry systems whose bulk density ranged between 1.267–1.298 Mg/m^3). Bulk density significantly increased (P = 0.001) with increase in soil depth.

We also found out that bulk density was significantly higher (P = 0.001) on farms with Robusta coffee compared to those with Arabica coffee. For both Arabica and Robusta coffee, the agroforestry farms had higher organic carbon than coffee mono crop farms (Fig. 2). Overall, SOC under Arabica- and Robusta- coffee agroforestry system was higher by 2.627 and 3.331 tC/ha compared to farms with no trees respectively. Robusta coffee farms had higher soil organic carbon at all depth compared to Arabica coffee (Fig. 3).

The results indicate that there are significant (P = 0.001) differences in soil organic carbon between coffee agroforestry farms and coffee monocrop farms. We also observed significant (P = 0.003) differences in SOC between farms with Arabica and Robusta coffee. Robusta coffee farms had higher soil organic carbon compared to Arabica coffee farms. Soil organic carbon did not significantly differ along depth. There was relatively more organic carbon found in the top 0–15 cm compared to 15–30 cm. There was a significant interaction (P = 0.000) between type of coffee and presence or absence of trees on farm (Table 2). An interaction plot was drawn to display this result (Fig. 4). It shows that soil organic carbon was higher under a mixture of, fruit trees, non-fruit trees and Robusta coffee than when those tree species were under Arabica coffee. Robusta coffee Agroforestry systems with non-fruit tree species had relatively higher SOC compared to other cropping systems. Arabica coffee stores more SOC when intercropped with fruit trees than Robusta coffee when integrated with the same trees. Under the coffee monocrop, Robusta coffee stores more SOC than Arabica coffee (Fig. 3). The results from the graph indicate the SOC is influenced by type of coffee and the type of trees present on farm.



Values on the horizontal axis represent the mean of soil organic carbon

Fig. 2. Soil organic carbon tC/kg under agroforestry system and mono coffee.

4. Discussion

4.1. Coffee agroforestry system and coffee monocrop system

Coffee agroforestry system farms had significantly higher SOC compared to coffee monocrop. Our findings corroborate Dossa et al. (2008) who found that shaded coffee system yield higher belowground biomass than open-grown coffee. Similarly Hergoualc'h et al. (2012) found that coffee agroforestry system with leguminous tree species had higher soil carbon stocks than coffee monoculture. In another related study by Thomazini et al., (2015), soil organic carbon was found to be greater in sites with developed vegetation communities.This may be attributed to continuous input of leaves, foliage and dead roots by the shade trees and coffee. Studies conducted on carbon sequestration potential in agroforestry system reveal that the linear simultaneous agroforestry systems have a significant potential to store more soil organic carbon compared to plots with no trees or crop only (Tumwebaze et al., 2011). Similarly Schmitt-Harsh et al. (2012) reported that shade trees in coffee plantations play an important role in facilitating carbon sequestration and soil conservation. Agroforestry systems in which high amounts of organic materials are added to the soil, such as shaded perennial-crop systems, have higher potential for sequestering carbon in the soil compared to treeless systems (Oelbermann and Voroney, 2007). However, the extent to which organic material is deposited depends on both species (the crop and shade tree) and the management system involved (Gama-Rodrigues et al., 2011). The amount of SOC in a system also depends on local climatic and management conditions (Gama-Rodrigues et al., 2010).

SOC is protected from decomposition through physical stabilization in an agroforestry system compared to monocrop system (Takimoto et al., 2009) even when the soils do not differ in characteristics such as pH (Takimoto et al., 2008) and bulk density. The current study therefore confirms the importance of integration of trees in coffee systems for enhancement of soil carbon sequestration potential.

4.2. SOC along the soil depth

There was no significant difference in the SOC between the two soil depths (0–15 cm and 15–30 cm). Similar observations were reported by Zinn et al. (2005) who found that in non intensive systems SOC stocks are not significantly different between 0 and 20 cm and 0–40 cm depth. Noponen et al. (2013) also found no significant differences between in SOC stocks between shaded and full-sun systems at any soil depth. The lack of any significant difference in the two layers may be due to cover provided by the coffee shrubs that protect the soil surface and lack of tilling in coffee plantations. In their studies Maia et al. (2010) found that perennial crops such as coffee as in the current study prevent loss of SOC and therefore this may explain the relatively no significant difference in SOC in the two layers investigated. The findings imply that the expected loss of SOC especially in the upper layer that may have occurred during land preparation for coffee planting had been restored by the time the inventory was done. The finding negates the often stated argument that SOC under agricultural land is not reliable because of changes that may be associated with ploughing during land preparation (Jobbágy and Jackson, 2000).

4.3. Soil organic carbon under Robusta and Arabic coffee

Robusta coffee farms had higher soil organic carbon at all depth compared to Arabica coffee under either agroforestry or coffee monocrop system. This is attributed to higher aboveground biomass produced by Robusta coffee compared to Arabica

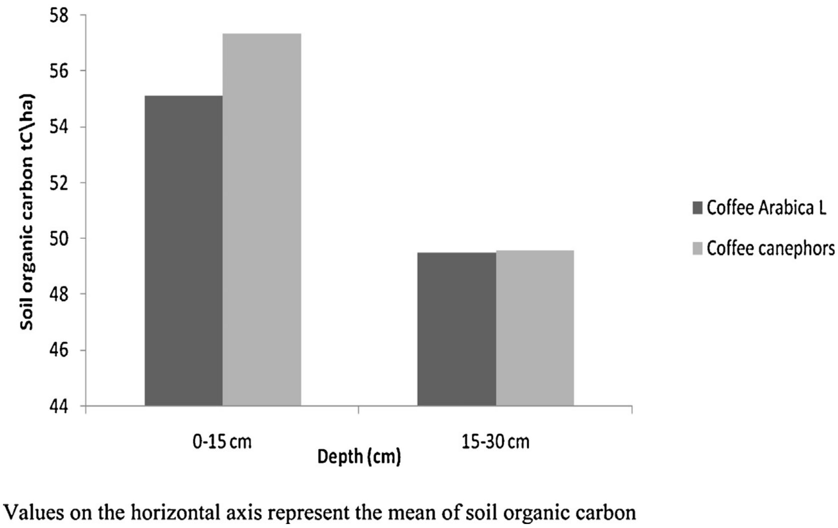


Fig. 3. Soil organic carbon tC/kg per depth and coffee species.

Table 2
Output of mixed model analysis of SOC.

Terms	Wald statistics	Numerator degrees of freedom	*F* statistics	Denominator degrees of freedom	*F* probability
Depth of soil	19.11	1	19.11	1.4	0.093
Type of coffee	1.6	1	1.6	784	0.206
[a]Trees present on farm	18.21	3	6.07	784	<0.001
Depth × type of coffee on farm	0.24	1	0.24	784	0.625
Depth × trees present on farm	0.05	3	0.02	784	0.997
[a]Type of coffee × trees present on farm	25.38	3	8.46	784	<0.001
Depth × type of Coffee on farm × trees present on farm	0.1	3	0.03	784	0.992

[a] Indicates the terms that were significant at 5% significance level.

(Wairegi et al., 2014). Arabica coffee consists of fewer trunks while Robusta coffee has multiple trunks Vieira (2008) that contribute to more above ground biomass compared to Arabica. Some studies (e.g. DaMatta, 2004; Vieira, 2008) noted that Robusta coffee is more resistant to unfavourable conditions and productive than Arabica, though the former is perceived to produce better quality beans that attract a better premium. This therefore may explain the relatively higher SOC under Robusta coffee than Arabica.

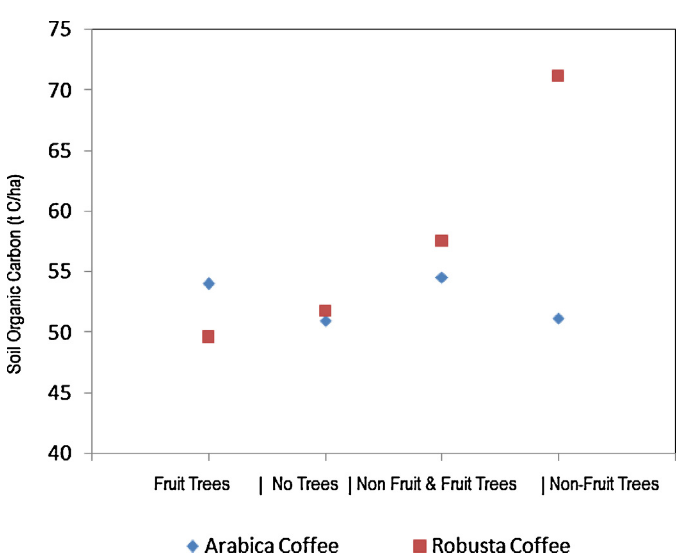


Fig. 4. Interaction plot of SOC (tC/kg) coffee type and trees on farm.

5. Conclusion and Recommendations

The current study shows that coffee agroforestry systems have potential to sequester more SOC than coffee monocrop. Robusta coffee agroforestry system with non-fruit trees have better potential to sequester SOC compared to Arabica coffee agroforestry system with similar tree species. Arabica coffee sequesters more SOC when intercropped with fruit trees such as *A. heterophyllus* Lam., *P. americana* Mill. and *M. indica* L.. Under coffee monocrop, Robusta coffee sequesters more SOC than Arabica coffee. The study recommends that in order to harness soil organic carbon credits farmers ought to be encouraged to practice coffee agroforestry system that integrates trees compared to coffee monocrops. There is need for policy incentives that encourage the planting and maintenance of shade trees in coffee plantations for the benefit of carbon sequestration. It is therefore our considered opinion that as developing countries prepare themselves to tap from existing global carbon credit schemes such as REDD+, CDM and other voluntary carbon schemes, coffee agroforestry systems should be prioritized as a reliable option of climate mitigation because its benefits are double pronged (contributes directly to household income and carbon sequestration).

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