Examining the contributions of maize shoots, roots, and manure to stable soil organic carbon pools in tropical smallholder farming soils

Blessing Nyamasoka-Magonziwa[1*]; Steven J. Vanek [1]; John O. Ojiem [2] & Steven J. Fonte [1]

[1]*Department of Soil and Crop Sciences, Colorado State University, Fort Collins, Colorado, USA.*
[2]*Kenya Agriculture and Livestock Research Organization, Kisumu, Kenya.*

**Corresponding author: Blessing Nyamasoka-Magonziwa*
email: Blessing.Magonziwa@colostate.edu

Abstract

Continuous inputs of organic matter are vital for sustaining soil organic carbon (SOC) and productivity of soils in smallholder crop-livestock systems. However, the dynamics of the different inputs i.e. maize shoots, roots and manure used are poorly understood. Along with organic inputs, use of mineral fertilizers can alter the nutrient stoichiometry of organic matter inputs and have implications for SOC turnover. This study sought to understand how maize-based inputs and alterations to nutrient stoichiometry contribute to stable SOC pools. We hypothesized that higher quality litter (i.e., manure) contributes more than maize residues to stable SOC pools and that N, P and S additions, designed to balance the stoichiometry of inputs to reflect the stable fine fraction of soil organic matter (C:N:P:S-10,000:833:200:143) results in greater SOC stabilization. We used a ^{13}C natural abundance approach, where the C4 maize residues were incubated for 11 months to trace C stabilization into different SOC pools within a C3 soil. Contrary to our expectations, we observed greater recovery and stabilization of shoot-derived C (2 X more than manure and 1.63 X more than roots) in the mineral-associated organic matter (MAOM) fraction. Mineral N, P and S additions reduced new C recovery in MAOM by 40% compared to no mineral nutrient's additions. Our study highlights the importance of residue retention as a strategy to maintain SOC and soil health in smallholder systems, and our results challenge the idea that nutrient additions increase C stabilization of added residues.

Key words: mineral-associated organic matter, C stabilization, root derived C, ^{13}C natural abundance

1 Introduction

Smallholder farming systems often face challenges of low availability of organic matter and nutrient inputs, with long-term implications for soil health and soil organic carbon (SOC) stocks (Tittonell et al. 2005; Rusinamhodzi et al. 2015). As a key indicator of soil fertility, SOC is crucial for the maintenance of soil health and for supporting crop yields in smallholder farming communities (Batiano et al. 2007). Concerns over current soil health trends have led to the promotion of agricultural practices such as reduced tillage, organic matter additions, residue retention, legume incorporation and agroforestry to help reverse soil degradation (Ojiem et al. 2006; Mungai et al. 2016). By enhancing organic matter inputs and/or slowing the loss of SOC via decomposition, these practices have the potential to significantly improve long-term SOC dynamics in smallholder soils (Chenu et al. 2019).

Smallholder farmers often manage an array of organic inputs in their fields, but maintaining SOC stocks, even under conservation agriculture and other SOC supporting practices mentioned above, can still present a significant challenge (Sommer et al. 2018). In many smallholder systems of sub-Saharan Africa, crop residues are often retained in-field or transferred to other plots to support soil fertility and SOC (Rusinamhodzi et al. 2015; Berazneva, et al. 2018). In mixed crop-livestock systems, however, there is competition for residues that often favors feeding livestock and then applying the manure to the field (Castellanos-Navarrete et al. 2015). The fate of crop residues likely has important implications for SOC dynamics; however, it remains unclear whether applying crop residues directly to fields is more effective at building SOC than feeding this material to animals and then returning what C remains to the field as manure (Rufino et al. 2011; Rodriguez et al. 2017). Moreover, there continues to be considerable uncertainty surrounding the role of belowground inputs (i.e., roots and other rhizodeposits) in maintaining SOC, even though roots may be the most important source of C inputs in many farming systems. Root-derived C is thought to be preferentially stabilized in soils due to the release of labile C exudates and the presence of aliphatic compounds that are more easily assimilated in microbial biomass C (Rasse et al. 2005; Jackson et al. 2017), as well as their close proximity with soil particles which allows them to more likely become associated with mineral surfaces (Schmidt et al. 2011). While our knowledge for SOC dynamics and stabilization from different C sources is improving, tropical soils and smallholder agricultural systems remain understudied and additional research is needed to generate more concrete residue management recommendations for supporting soil health and long-term productivity on smallholder farms.

Residue inputs are known to contribute to SOC and overall soil health, however, knowledge gaps remain on the role of residue quality and the influence of mineral fertilizer additions on SOC dynamics. Studies by Chivenge et al. (2011) and Puttaso et al. (2011) noted that the quality of organic inputs influenced stabilization of C in slow and passive SOC pools. Furthermore, Chivenge et al, (2011) suggested that smallholder farmers have more access to low quality organic resources (in terms of C:N ratio) such as maize shoots, but these are often presumed to contribute less to SOC compared to residues with higher N content, such as manure (Kapkiyai et al. 1999). It should also be noted that the choice to apply manure versus shoots for supporting soil health is not just governed by the need to improve soil fertility, but by the need for livestock feed and other competing uses of residue and norms management (Rodriguez et al. 2017; Nyamasoka-Magonziwa et al. 2021). Related to the role of residue quality, additions of mineral fertilizer can influence SOC dynamics. For example, Kirkby et al. (2013; 2014) found that additions of mineral N, P, and S together with organic inputs can increase the amount of new C stabilized in soil. They suggested that strategic application of mineral nutrients to match the

C:N:P:S stoichiometry of the stable fine-fraction of soil organic matter (i.e., C:N:P:S-10,000:833:200:143) would result in the greatest degree of SOC stabilization. Generally speaking, residues with nutrient stoichiometries that more closely match that of microbial biomass are thought to be more efficiently assimilated by microbes; in essence, when residues are overly C-rich, microbes are more likely respire off this ‘extra’ C in order to better match their stoichiometry with that of their substrate. The fine-fraction refers to the SOC pool that has reached near constant ratios of C:N:P:S and is very slow to decompose (Kirby et al. 2013; Cotrufo et al. 2015; Basile-Doelsch et al. 2020). This pool is thought to be largely microbially-derived, therefore Kirby et al. (2013) suggest that by using nutrient additions to better match the stoichiometry of residues with microbial biomass (and the stable carbon fraction) more residue C becomes assimilated within the microbial biomass, and thus eventually becomes part of the stable SOC pool. However, this mechanism of stabilization remains poorly understood and has received little attention in tropical smallholder contexts.

Soil organic matter (SOM) is comprised of distinct pools, which can be distinguished via diverse fractionation approaches that can provide insight on the overall dynamics of SOC. For example, density-based fractionations typically involve separation of a light fraction, which is a more active C pool of less-decomposed plant material and can be easily degraded by microbes, versus a heavy fraction, which represents a more passive SOC pool and is thought to be more microbially-derived and associated with mineral surfaces (Cotrufo et al. 2020; Lavalle et al. 2019). While the active SOM pool is important for providing crops with readily available nutrients and perhaps offers a more rapid assessment of soil health changes in the short-term (Barrios et al. 1997; Nyamasoka-Magonziwa et al. 2020), it is the passive pools that reflect more stable C and long-term SOM accrual. Beyond heavy and light fractions, soil aggregation can also play an important role in SOC turnover, and it can be helpful to further separate organic matter that is occluded within aggregates versus that occurring freely in the soil (Six et al. 2002). In this study we focus on three fractions that reflect both density and size separations: 1) a light fraction, comprised of free particulate organic matter (fPOM), 2) a heavy fraction comprised of organic matter occluded within aggregates (i.e. occluded particulate organic matter; oPOM), and 3) mineral-associated organic matter (MAOM) that is smaller in size and not necessarily occluded within aggregates. Free POM is mostly plant-derived and formed from the fragmentation and depolymerization of organic inputs, with a mean residence time of less than a decade (Cotrufo et al. 2015). MAOM on the other hand, is derived more from microbially-processed organic matter and has a mean residence time of decades to centuries. At the same time oPOM, is thought to be less readily accessible to microbes than fPOM and likely represents a pool with intermediate rates of turnover and nutrient release (Wander and Yang, 2000).

Despite the documented benefits of crop residue inputs in smallholder farming contexts (Turmel et al. 2014; Rusinamhodzi et al. 2016), numerous questions remain as to the most effective ways to build SOM and efficiently manage tradeoffs in organic resources within many smallholder systems. Improved clarity on the possible mechanisms for increasing SOC stabilization (i.e., via crop residue type and addition or balancing of nutrient stoichiometry) is crucial to building SOC and supporting long-term soil health and productivity in smallholder systems in the tropics. Therefore, the goal of this study was to understand how varying forms of maize-based organic matter inputs contribute to SOC dynamics in smallholder farming contexts. Specifically, we used an incubation experiment and a ^{13}C a natural abundance approach to: 1) assess the incorporation of maize shoots versus maize-derived cattle manure into distinct soil SOC pools (mentioned above); 2) compare the potential contribution of maize root-derived C relative to maize shoots to key soil C pools; and 3) determine if balancing the stoichiometry of residue inputs by adding mineral forms of N, P, and S, to match that of the stable fine-fraction, improves the stabilization of SOC in a tropical soil. We hypothesized that manure derived-C is stabilized more readily compared to maize shoots due to the higher quality (lower C:N ratio) of this material. We also hypothesized that that additions of N, P and S enhance C stabilization for all types of inputs, and especially for the MAOM pool that is thought to be more dependent on microbial activity.

2 Materials and Methods

2.1 Study approach

An incubation experiment was carried out at the Kenya Agriculture and Livestock Research Organization (KALRO) center in Kibos, Kenya. The experiment relied on ^{13}C natural abundance differences between residues derived from maize (*Zea mays*), a C4 plant, and soil from a nearby forest dominated by C3 vegetation.

Soil was collected from the A horizon (5-20 cm depth) at a site in the Nandi Hills (N 00°05.034’ and E 034°58.580’), which was under relatively undisturbed C3 forest for at least 100 years prior to sampling. At roughly 2000 m in elevation, this site has an annual precipitation of 1800 mm and temperature range of 18-24 °C. Soils from this region are generally classified as ferralsols or nitisols (FAO 1988). Upon return to the laboratory, soil was passed through a 2 mm sieve, thoroughly mixed, and air-dried prior to the start of the incubation. The collected soil had an SOC content of 4.2 %, $\delta\ ^{13}C$ signature of -24, and a pH of 4.6 (measured in a 2:1 deionised water:soil suspension).

2.2 Experimental design and establishment

The experiment was comprised of three residue treatments with different types of maize-based residues incorporated into small pots containing the forest soil mentioned above. These treatments comprised additions of: 1) maize shoots, 2) maize roots (collected from a nearby field), 3) manure (from cattle fed solely with maize shoots), and 4) a control with no residue additions Additionally, each of the residue treatments were applied with or without mineral fertilizer additions to achieve a C:N:P:S stoichiometry of 10,000:833:200:143 for each residue type (see Table 1 and additional detail below). The fertilized control (i.e., no residue) treatment received N, P, and S additions equivalent to the maize shoot treatment, the latter requiring the greatest addition of mineral N, P, and S additions to achieve the desired stoichiometry. This resulted in full factorial design with eight treatments (four residue treatments x two fertilizer/stoichiometry levels) each with five replicates and arranged in a completely randomized design.

Forty plastic 4 L pots (20 cm height x 15.5 cm diameter) were each filled with 3.6 kg of a soil-sand mixture (2:1 soil:sand ratio by volume; the sand was added to help provide drainage) and the mixture packed down gently to achieve a bulk density of approximately 1.2 g cm^{-3}. The forty pots were maintained without any residue additions during a 5-week preincubation stage. All pots were maintained at similar moisture and temperature levels by weighing a representative sub-sample of pots on a weekly basis and adding the average amount of water required to achieve 80 % of field capacity.

For treatments with maize shoots and roots, mature maize plants were collected from a farm in Nandi (close to where forest soil was collected) by excavating and uprooting the whole plant. The roots were cleaned by rinsing with tap water and passing the soil water slurry over a fine mesh and then air-dried. A subsample of the roots and shoots were then oven-dried at 60 ^{o}C to determine the air-dried to oven-dry biomass conversion for roots and shoots, separately.

Remaining air-dried shoots and roots were chopped to < 8 mm in size. In order to obtain manure with a pure C4 signature, two cows under zero-grazing were fed with pure maize stover for 3 days. The manure produced in the first 2 days was discarded and manure produced on the third day was collected, assuming that most of this would reflect the maize consumed over the previous 2 days. This material was air-dried, broken apart by hand and passed through an 8 mm sieve, while a sub-sample was oven-dried to determine the moisture content.

Samples of each residue type were sent to a commercial laboratory in Nairobi, Kenya, for characterization of total N using Kjeldahl acid digestion, total P and total S using microwave digestion with nitric acid and hydrochloric acid and analyzed with Optical Emission spectrometry (ICP-OES), as well as total C according to the Walkley-Black chromic acid wet oxidation method. Results from the laboratory were used to determine rates of N, P and S additions for all residue treatments (Table 1).

After 5 weeks for preincubation, organic inputs (shoots, manure, roots) were incorporated at an oven-dry rate equivalent to 12 Mg ha^{-1} (or 27.7 g air dried biomass pot^{-1}) to pots with the homogenized C3 forest soil. Treatment specific additions of N, P and S (Table 1) were applied to half of the pots at the same time as the residues to achieve uniform stoichiometry across all treatments equivalent to C:N:P:S- 10,000:833:200:143, so as to mirror the stoichiometry of the stable fine fraction of soil organic matter as reported by Kirkby et al. (2013). Mineral N, P, and S were comprised of triple super phosphate (TSP), calcium ammonium nitrate (CAN), and ammonium sulfate fertilizer. Pelletized fertilizer was ground and weighed separately for each treatment prior to application. All pots were mixed with a trowel, including the control treatment, to incorporate residue and mineral nutrient additions and approximate a uniform level of soil disturbance across all treatments.

Upon full treatment implementation, the pots were kept in a dark room and maintained at roughly uniform moisture by weighing a sub-sample of pots from each treatment and adding water to bring them up to 60 % field capacity every two weeks for a period of 48 weeks. While the room was not climate controlled, the space was selected to approximate outside temperatures of a typical shaded surface soil in the region.

2.3 Sampling and analysis

At harvest, each pot was emptied out and passed through an 8 mm sieve by gently breaking large soil aggregates along natural planes of weakness. The soils were then air-dried, and a representative sub-sample shipped to Colorado State University and quarantined until further processing. The samples were de-quarantined by transferring soils to pre-weighed aluminum pans, weighing and heating for 24 hours at 115°C, then cooled and then sieved to 2 mm. This follows methods outlined by Haddix et al. (2020), who found the heating treatment to not significantly affect C content of the different fractions.

2.4 Fractionation procedure

In order to better understand the decomposition and stabilization dynamics of the added residues we separated the soils into three C density/size fractions (Fig. 1) according to Soong and Cotrufo (2015). In brief, a 10.5 g sub-sample of soil was separated by density fractionation using sodium polytungstate (SPT) at 1.85 g cm^{-3} to isolate the free particulate organic matter (fPOM) that floated to the top after 30 min. in a centrifuge (at 3400 rpm) at 20 °C. The fPOM floating at top was the aspirated and collected on a 20 μm nylon filter and allowed to oven dry at 60 ^{o}C. The denser material settling at the bottom was then shaken with 0.5 % sodium hexametaphosphate for

18 hours to disperse aggregates and then passed through a 53 μm sieve to separated occluded POM (oPOM), which is >53 μm, from the mineral-associated organic matter (MAOM), which is <53 μm. Occluded POM is thought to represent POM that was trapped in aggregates (along with some sand particles). The fractions were collected in aluminum pans and dried in an oven at 60 ^{o}C.

2.5 Isotopic analyses and calculations

Subsamples from all fractions and the bulk soil were ground and sent to the UC Davis Stable Isotope Facility for analysis of ^{13}C, as well as total C and N using a Micro Cube elemental analyzer (Elementar Analysensysteme GmbH, Hanau, Germany) interfaced to a PDZ Europa 20-20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK). Subsamples of the different organic residues and C3 forest soil were also sent to the UC Davis Stable Isotope Facility for isotopic and elemental analysis.

A mixing model was used to determine the proportion of maize-derived (C4) C present in the soil fractions and bulk soil (equation 3.1).

$$f\ value = (\delta soil - \delta na)/(\delta input - \delta na) \qquad (3.\ 1)$$

where f value is the proportion of C from the C4-derived organic residue, δsoil is the ^{13}C signature of the soil fraction or bulk soil after incubation, δna is the ^{13}C value for the relevant soil fraction or bulk soil in the control treatment (no residues added), δinput is the ^{13}C of the added maize-derived residue.

In order to account for the different amounts of C added in each residue treatment (due to varying C concentrations of the three residue types; Table 1) the proportion of maize-derived C that was stabilized for each fraction was corrected to account for the total amount of C added in each treatment and calculated as follows:

$$New\ C = (C\ concentration * f\ value)/C\ input \qquad (3.\ 2)$$

where *New C* is the proportion of added C that was stabilized, *C concentration* is the concentration of C of each fraction (g C kg^{-1} soil), and *C input* is the amount of C that was added in each treatment, on a g C kg^{-1} whole soil basis. This new C was calculated both on per soil fraction basis (i.e. fPOM, oPOM, and MAOM), which allowed for a mechanistic understanding of dynamics in individual fractions, as well as on a whole soil basis, to understand how these changes related to overall SOC dynamics.

2.6 Statistical analysis

Two-way ANOVA was used to examine the effect of residue type, nutrient addition, and the nutrient by residue interaction on C content, f values, New C and the C:N ratio of each soil fraction and the bulk soil. Assumptions of ANOVA were examined, and ln or square root transformations applied as needed. All analyses were conducted using JMP Pro 15.0 software (SAS Institute, 2019).

3 Results

3.1 Treatment effects on total C and C:N ratio

Of the three fractions, fPOM was generally the most enriched in total C (range: 204-232 g C kg $^{-1}$ soil fraction), followed by MAOM (range: 43.5-45.3 g C kg $^{-1}$ soil fraction) and then oPOM (range: 4.80-5.85 g C kg $^{-1}$ soil fraction), while bulk soil ranged from 26.7-31.1 g C kg $^{-1}$. Residue type and nutrient addition did not significantly affect total soil C concentrations for any of the fractions (Table 2). Also, we note that total C within the different fractions on a whole soil basis did not differ significantly among treatments. Overall, the MAOM fraction contained most of the SOC (i.e., over 80 % of total SOC across all treatments).

Nutrient additions lowered the C:N ratio of bulk soil (p = 0.005; Table 2) with a tendency for manure and root inputs to be reduced more than shoots by nutrient additions (nutrient by residue interaction, p = 0.062). At the same time no effects of residue type nor nutrient additions were evident for the C:N ratio of the fPOM, and oPOM fractions. MAOM had the lowest and narrowest range of C:N ratios (12.0-12.3) compared to oPOM (12.6-13.3) and fPOM (19.4-24.1).

3.2 Recovery of maize-derived C in soil fractions

Residue type had significant effects on $\delta^{13}C$ values in MAOM and bulk soil fractions, such that the manure and root treatments (with and without fertilizer) had lower maize-derived residue (indicated by more negative values) than maize shoots (Table 3). Nutrient additions only had significant effects in the MAOM fraction, such that adding nutrients led to slightly lower maize-derived C (more negative $\delta^{13}C$ values) than without nutrient additions. There was a significant residue type by nutrient interaction for the oPOM fraction (p = 0.02), such that the addition of nutrients resulted in less maize-derived C for the root and manure treatments, but more maize derived C when maize shoots were added.

Following from the observed differences in ^{13}C values and different amounts of C input across treatments, the proportion of C from the added inputs (i.e., f value; Table 3) was significantly affected by residue type in MAOM and bulk fraction, where manure treatments had lower f values compared to the other treatments. Contrary to our hypothesis, nutrient additions resulted in significantly lower f values (p = 0.012) across treatments for the MAOM fraction. There was also a significant residue by nutrient interaction for oPOM (p = 0.014), such that a higher proportion of shoot-derived C was found in this fraction in the presence of nutrient additions, while nutrient additions tended to decrease f values for root- and manure-derived C inputs.

When looking at new C derived from residue additions in the different C pools on a per fraction basis (and corrected for differences in total C input), fPOM was highly variable within and across treatments ranging from 7.2 to 19.1 g C kg^{-1} fraction g^{-1} C added with no significant treatment effects (Table 3). For the oPOM fraction, there were no simple effects of residue type or nutrient addition, but there was a significant residue by nutrient interaction ($p = 0.044$), where nutrient additions tended to increase the amount new C recovered in maize shoot fraction, but decreased new C for manure and roots. New C in the MAOM fraction was significantly influenced by both residue type ($p = 0.008$) and nutrient additions ($p = 0.009$; Fig. 2). Averaged across nutrient additions, shoot-derived C was stabilized into MAOM at twice the rate of manure-derived C and 1.6 times more than root C (Fig. 2a), while nutrient additions (averaged across residue type) decreased C stabilization in MAOM by roughly 40% relative to that observed in the absence of nutrients (Fig. 2b).

New C on a whole soil basis (i.e., taking into account the relative contribution of each fraction to the whole soil mass) did not differ significantly for fPOM and oPOM, but residue type influenced new C present in the MAOM fraction ($p = 0.011$) with shoots having the highest amount of new C stabilized (2.2 and 1.7 times more new C than for manure and ex-situ roots; respectively), while addition of nutrients showed a marginally significant ($p = 0.068$) effect on C stabilization in MAOM, indicated a 30% reduction on a whole soil basis, relative to soils with no fertilizer addition (Table 3). We note that most new C in manure and root treatments was found in fPOM, while most new C from shoots was found in the MAOM fraction.

4 Discussion

Our study sought to understand how different types of maize-based organic matter inputs (shoots, roots, and manure) contribute to distinct soil fractions and overall SOC stabilization within smallholder farming contexts and whether nutrient additions to balance the C:N:P:S stoichiometry of residues and optimize their incorporation into microbial biomass would enhance C stabilization of distinct organic inputs.

4.1 Residue quality as a driver of SOC dynamics

Our findings indicate that while different organic residue types resulted in minimal impacts on fPOM and oPOM fractions, maize shoot-derived C appears to be preferentially retained in the MAOM fraction relative to C derived from maize roots or manure. This is relevant, since MAOM has the slowest turnover of SOC for the soil fractions we evaluated, and C recovered in this fraction can be thought of as stabilized SOC. It is also worth noting that we found the MAOM fraction to comprise ~80% of the total bulk SOC. Because MAOM is the largest SOC pool, it has been noted to be highly and positively correlated to total SOC (Cotrufo et al. 2019), such that behavior of C in the MAOM fraction likely reflects the behavior of SOC in the whole soil.

The higher stabilization of shoot-derived C in MAOM may be attributed to several mechanisms related to the biochemical composition and overall quality of residues. For example, some authors have suggested that materials with lower C:N ratios, such as manure in this study, may be more readily stabilized compared to lower quality residues (e.g., coarse roots and shoots) since they tend to result in a high microbial C use efficiency (CUE), i.e., greater assimilation of C within microbes and decreased losses via respiration (e.g., Cotrufo et al. 2013; Dannehl et al. 2017). At the same time, Kallenbach et al. (2019) noted that in some cases, lower quality substrates can result in higher CUE at the community level by selecting for microbial taxa (e.g., fungi) that are more efficient at assimilating C. Other studies have noted that residue quality to have no effects on the stabilization of C in different fractions (Gentile et al. 2011). These apparently conflicting findings suggest that diverse mechanisms are at play and that organic matter turnover in soils is likely controlled by a variety of factors.

Additionally, residue quality involves more than just simple stoichiometric measures such as the C:N ratio, and refers also to the structural composition of organic matter (e.g., lignin content). Our study supports this idea since we balanced the stoichiometry to have equivalent C:N:P:S ratios across residue types and still found differences in C stabilization between manure and roots versus shoots. Therefore, there are likely other characteristics that influence SOC turnover and stabilization by soil microbes. Similar to our findings, Fulton-Smith and Cotrufo (2019) conducted an incubation with sorghum shoot versus ex-situ root residues and found that shoots resulted in greater new C in MAOM than roots. They attributed this to litter chemistry, in that shoots had a lower lignocellulose index (i.e., ratio of acid non-hydrolysable to non-hydrolysable + hydrolysable products) than roots and may thus affect microbial decay of residues and CUE. Both the lignocellulose index and lignin content have been shown to be the good predictors of organic matter decomposition processes (Palm et al. 2001; Moorhead et al. 2014). This emphasizes the importance of considering lignin content, or the lignin:N ratio, and not just the C:N ratio in models predicting C stabilization. While not measured in this study, manure generally has higher lignin content (18.2 %-50 %) than maize shoots and maize roots (12 % to 18 %; Abiven et al. 2011; Beyaert and Voroney 2011, Yan et al. 2018; Zhu et al. 2020) and this generally aligns well with the patterns we observed for SOC dynamics in our study.

The finding of relatively lower stabilization of root-derived C compared to shoot-derived C contrasts with other studies (e.g., Rasse et al. 2005; Kong and Six 2010; Sokol et al. 2018; Hui Xu et al.2019; Sokol and Bradford 2019), which highlight the importance of root-derived C, and suggest a 2 to 13-fold greater stabilization for root than for shoot-derived C. The lower stabilization of root-derived C in our study is likely related to the fact that we used ex-situ roots. Important mechanisms of SOC stabilization that are unique to roots growing in place, such as being in close proximity to soil particles, effects on aggregation and release of high-quality root exudates (and other rhizodeposits), were not tested here and therefore limit our conclusions regarding the contributions of roots to stable SOC.

4.2 Balancing C:N:P:S stichometry

In contrast to our hypothesis, we found that adding mineral forms of N, P, and S to balance the C:N:P:S stoichiometry of the added residues led to a general decrease in C stabilization in the MAOM fraction. Therefore, our results appear to contradict those of Kirkby et al. (2013), who found that balancing the stoichiometry resulted in more C stabilization of wheat straw in the fine stable fraction (comparable to MAOM in this study) during an 84-day incubation in soils from Australia. While few studies have examined the co-application of N, P and S on SOC dynamics, our results are broadly in line with the findings of Chivenge et al. (2011), who found that adding N fertilizer with residues resulted in lower SOC stabilization in stable aggregate fractions. Similarly, Fonte et al. (2009) reported a reduction in aggregate-associated C with fertilizer additions to soil in Ghana. Along these same lines, Chen et al. (2020) reported that addition of mineral N led to a decrease in C in the mineral-associated fraction due to the inhibition of microbial activity and hence a reduction in microbial biomass C. While these studies did not seek to perfectly balance nutrient stoichiometry as was done in this experiment, others have found that doing so can lead to a decreased C in soils in the long term. For example, Fang et al. (2019) applied N, P and S during a 245-day incubation and suggested that while balancing stoichiometry may result in better nutrient use efficiency and increased microbial biomass in the short term; there might be increased decomposition of the C in the long-term due to more active microbial populations, leading to an overall decrease in SOC. Our study was 335 days, had we measured the effect of nutrient additions earlier in the experiment, we might have seen greater stabilization with N, P, and S additions, as reported by Kirby et al. (2013).

4.3 Implications for crop-livestock systems in smallholder farming systems

Farmers often feed crop residues to their animals and then apply manure to their cropping fields rather than retaining the residues in the field (Castellanos-Navarrete et al. 2015; Nyamasoka-Magonziwa et al. 2021). This choice has potentially important implications for maintaining SOM and the long-term productivity of soils. However, surprisingly little is known about the fate of residue versus manure C additions to soil fractions, and which type of input best supports SOC in the long-term. We must also consider that feeding crop residues to animals decreases the amount of C being returned to soils, since livestock assimilate and respire much of what they eat, and only about 45% of the C fed to animals can be returned to the soil as manure (Nennich et al. 2006). Nevertheless, even beyond this initial C loss due to livestock respiration and assimilation, our findings suggest that C added to the soil as manure may actually result in lower stabilization of SOC than C added in stover. If we further consider the benefits of maintaining crop residues on the soil surface, especially as mulch (e.g., erosion control, reduced evaporative losses), then this implies clear tradeoffs for soil health. Considering, however, that livestock are important (for household nutrition, food security, investments, etc.) and crop residues may provide critical feed during times of forage scarcity, the decision to retain residues or feed to livestock is not straightforward. While our findings are not conclusive, they raise important concerns about what residue management strategies should be promoted by extension and development organizations to support soil health (Rodriguez et al. 2017). Despite our findings indicating lower stabilization of manure derived-C, manure can still play important role in managing soil health, as manure is likely to support overall crop nutrition and key soil properties (e.g., soil aggregation) better than crop residues (Dunjana et al. 2012; Miller et al. 2012; Yagüe et al. 2016). Manures, at least those of high quality, also tend to release nutrients faster than crop residues (Reddy et al. 2008) and thus can provide better synchrony between nutrient release and crop nutrient demands, especially in the absence of fertilizer inputs.

It should also be noted that in smallholder systems not all shoots produced on farm are cycled within the farm and that manure is often available only in small quantities. Therefore, root derived-C is the most reliable C source in these systems, as it is left in field after the shoots are harvested or added as exudates during the growing season. Considering the noted potential of root-derived C to contribute to SOC stabilization, efforts should be made to better understand this key organic matter input and explore options to increase root biomass in smallholder farming systems. This can be done by adopting systems that allow for active roots to be maintained during a greater portion of the year (e.g., crop rotations with perennial forages) or crop varieties with more vigorous roots systems, but without compromising crop yields. Finally, while mineral fertilizer additions may play a positive role in building SOC by supporting crop growth and increased overall C inputs (Zhang et al. 2015), the effects of nutrient additions on MAOM observed here (and in other studies noted above) may counteract potential increases to productivity and C inputs.

5 Conclusion

Our findings indicate that strategies for SOC stabilization in smallholder systems are not always straightforward and are often complicated by tradeoffs in resource allocation. Contrary to expectations, our findings indicate that maize shoots may contribute more to stable SOC pools (i.e., MAOM) than ex-situ roots or manure. This highlights the potential importance of residue retention as a strategy to increase SOC content and long-term soil health. We note that this finding is still not conclusive, and we emphasize the need for additional research using ^{13}C enrichment approaches to provide more definitive information about the long-term fate of different residue types in soils, especially root-derived C and inputs from actively growing roots. Additionally, there is still need to further examine the effects of different residue types and nutrient additions on other soil health attributes and overall productivity, so as to have a more systems-oriented understanding of likely impacts on smallholder soils.

Acknowledgments

We thank staff at the Kenya Agricultural and Livestock Research Organization (KALRO) Horticulture center for their support. Specifically, we appreciate the support of Nancy Yahuma with monitoring and providing the research assistance in Kenya. At Colorado State University we thank Michelle Haddix and Laura van der Pol for their support with laboratory methods and support. This project was funded by the McKnight Foundation (grant number 15-533).

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

References

Abiven, S., Heim, A., & Schmidt, M. W. (2011). Lignin content and chemical characteristics in maize and wheat vary between plant organs and growth stages: consequences for assessing lignin dynamics in soil. Plant and Soil, 343(1), 369-378.

Barrios, E., Buresh, R. J., Kwesiga, F., & Sprent, J. I. (1997). Light fraction soil organic matter and available nitrogen following trees and maize. Soil Science Society of America Journal, 61(3), 826-831.

Basile-Doelsch, I., Balesdent, J., & Pellerin, S. (2020). Reviews and syntheses: The mechanisms underlying carbon storage in soil. Biogeosciences, 17(21), 5223-5242.

Bationo, A., J. Kihara, B. Vanlauwe, B. Waswa, and J. Kimetu. 2007. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agricultural Systems 94:13–25.

Berazneva, J., Lee, D. R., Place, F., & Jakubson, G. (2018). Allocation and valuation of smallholder maize residues in Western Kenya. Ecological Economics, 152, 172-182.

Beyaert, R., & Voroney, R.P. (2011). Estimation of decay constants for crop residues measured over 15 years in conventional and reduced tillage systems in a coarse-textured soil in southern Ontario. Canadian Journal of Soil Science, 91(6), 985-995.

Castellanos-Navarrete, A., Tittonell, P., Rufino, M. C., & Giller, K. E. (2015). Feeding, crop residue and manure management for integrated soil fertility management–A case study from Kenya. Agricultural Systems, 134, 24-35.

Chen, J., Xiao, W., Zheng, C., & Zhu, B. (2020). Nitrogen addition has contrasting effects on particulate and mineral-associated soil organic carbon in a subtropical forest. Soil Biology and Biochemistry, 142, 107708.

Chenu, C., Angers, D. A., Barré, P., Derrien, D., Arrouays, D., & Balesdent, J. (2019). Increasing organic stocks in agricultural soils: Knowledge gaps and potential innovations. Soil and Tillage Research, 188, 41-52.

Chivenge, P., Vanlauwe, B., Gentile, R., & Six, J. (2011). Organic resource quality influences short-term aggregate dynamics and soil organic carbon and nitrogen accumulation. Soil Biology and Biochemistry, 43(3), 657-666.

Cotrufo, M. F., Ranalli, M. G., Haddix, M. L., Six, J., & Lugato, E. (2019). Soil carbon storage informed by particulate and mineral-associated organic matter. Nature Geoscience, 12(12), 989-994.

Cotrufo, M. F., Wallenstein, M. D., Boot, C. M., Denef, K., & Paul, E. (2013). The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? Global Change Biology, 19(4), 988-995.

Dannehl, T., Leithold, G., & Brock, C. (2017). The effect of C: N ratios on the fate of carbon from straw and green manure in soil. European Journal of Soil Science, 68(6), 988-998.

Fang, Y., Singh, B. P., Cowie, A., Wang, W., Arachchi, M. H., Wang, H., & Tavakkoli, E. (2019). Balancing nutrient stoichiometry facilitates the fate of wheat residue-carbon in physically defined soil organic matter fractions. Geoderma, 354, 113883.

Fonte, S. J., Yeboah, E., Ofori, P., Quansah, G. W., Vanlauwe, B., & Six, J. (2009). Fertilizer and residue quality effects on organic matter stabilization in soil aggregates. Soil Science Society of America Journal, 73(3), 961-966.

Food Agriculture Organization (FAO) for the United Nations. (1998). World reference base for soil resources (Vol. 3). Food & Agriculture Org. ISBN 92-5-104141-5

Gentile, R., Vanlauwe, B., Kavoo, A., Chivenge, P., & Six, J. (2011). Residue quality and N fertilizer do not influence aggregate stabilization of C and N in two tropical soils with contrasting texture. Nutrient Cycling in Agroecosystems, 88, 121-131.

Haddix, M. L., Gregorich, E. G., Helgason, B. L., Janzen, H., Ellert, B. H., & Cotrufo, M. F. (2020). Climate, carbon content, and soil texture control the independent formation and persistence of particulate and mineral-associated organic matter in soil. Geoderma, 363, 114160.

Hall, S. J., Huang, W., Timokhin, V. I., & Hammel, K. E. (2020). Lignin lags, leads, or limits the decomposition of litter and soil organic carbo, .Ecology, 101(9), e03113

Jackson, R. B., Lajtha, K., Crow, S. E., Hugelius, G., Kramer, M. G., & Piñeiro, G. (2017). The ecology of soil carbon: pools, vulnerabilities, and biotic and abiotic controls. Annual Review of Ecology, Evolution, and Systematics, 48, 419-445.

Kallenbach, C. M., Wallenstein, M. D., Schipanksi, M. E., & Grandy, A. S. (2019). Managing agroecosystems for soil microbial carbon use efficiency: ecological unknowns, potential outcomes, and a path forward. Frontiers in Microbiology, 10, 1146.

Kapkiyai, J.J., Karanja, N.K., Qureshi, J.N., Smithson, P.C. and Woomer, P.L., 1999. Soil organic matter and nutrient dynamics in a Kenyan nitisol under long-term fertilizer and organic input management. Soil Biology and Biochemistry, 31(13), pp.1773-1782.

Kirkby, C. A., Richardson, A. E., Wade, L. J., Batten, G. D., Blanchard, C., & Kirkegaard, J.A. (2013). Carbon-nutrient stoichiometry to increase soil carbon sequestration. Soil Biology and Biochemistry, 60, 77-86.

Kirkby, C. A., Richardson, A. E., Wade, L. J., Passioura, J. B., Batten, G. D., Blanchard, C., & Kirkegaard, J. A. (2014). Nutrient availability limits carbon sequestration in arable soils. Soil Biology and Biochemistry, 68, 402-409.

Kong, A. Y., & Six, J. (2010). Tracing root vs. residue carbon into soils from conventional and alternative cropping systems. Soil Science Society of America Journal, 74(4), 1201-1210.

Lavallee, J. M., Conant, R. T., Paul, E. A., & Cotrufo, M. F. (2018). Incorporation of shoot versus root-derived 13 C and 15 N into mineral-associated organic matter fractions: results of a soil slurry incubation with dual-labelled plant material. Biogeochemistry, 137(3), 379-393.

Miller, J. J., Bremer, E., Beasley, B. W., Drury, C. F., Zebarth, B. J., & Larney, F. J. (2012). Long-term effect of fresh and composted cattle manure on the size and nutrient composition of dry-sieved soil aggregates. Canadian Journal of Soil Science, 92(4), 673-683.

Moorhead, D., Lashermes, G., Recous, S., & Bertrand, I. (2014). Interacting microbe and litter quality controls on litter decomposition: a modeling analysis. PloS one, 9(9), e108769.

Mungai, L. M., Snapp, S., Messina, J. P., Chikowo, R., Smith, A., Anders, E., ... & Li, G. (2016). Smallholder farms and the potential for sustainable intensification. Frontiers in Plant Science, 7, 1720.

Nennich, T. D., Harrison, J. H., VanWieringen, L. M., St-Pierre, N. R., Kincaid, R. L., Wattiaux, M. A., ... & Block, E. (2006). Prediction and evaluation of urine and urinary nitrogen and mineral excretion from dairy cattle. Journal of Dairy Science, 89(1), 353-364.

Nyamasoka-Magonziwa, B., Vanek, S. J., Carolan, M. S., Ojiem, J. O., & Fonte, S. J. Organic nutrient source allocation and use in smallholder farming communities: what are we missing? Frontiers in Sustainable Food Systems, 289.

Nyamasoka-Magonziwa, B., Vanek, S. J., Ojiem, J. O., & Fonte, S. J. (2020). A soil tool kit to evaluate soil properties and monitor soil health changes in smallholder farming contexts. Geoderma, 376, 114539.

Ojiem, J. O., De Ridder, N., Vanlauwe, B., & Giller, K. E. (2006). Socio-ecological niche: a conceptual framework for integration of legumes in smallholder farming systems. International Journal of Agricultural Sustainability, 4(1), 79-93.

Palm, C. A., Gachengo, C. N., Delve, R. J., Cadisch, G., & Giller, K. E. (2001). Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agriculture, Ecosystems & Environment, 83(1-2), 27-42.

Puttaso, A., Vityakon, P., Saenjan, P., Trelo-Ges, V., & Cadisch, G. (2011). Relationship between residue quality, decomposition patterns, and soil organic matter accumulation in a tropical sandy soil after 13 years. Nutrient Cycling in Agroecosystems, 89(2), 159-174.

Rasse, D. P., Rumpel, C., & Dignac, M. F. (2005). Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. Plant and Soil, 269(1-2), 341-356.

Reddy, K. S., Mohanty, M., Rao, D. L. N., Singh, M., Dalal, R. C., Rao, A. S., ... & Menzies, N. E. A. L. (2008). Nitrogen mineralization in a Vertisol from organic manures, green manures and crop residues in relation to their quality. Agrochimica, 52(6), 377-388.

Rodriguez, D., de Voil, P., Rufino, M. C., Odendo, M., & van Wijk, M. T. (2017). To mulch or to munch? Big modelling of big data. Agricultural Systems, 153, 32-42.

Rufino, M. C., Dury, J., Tittonell, P., Van Wijk, M. T., Herrero, M., Zingore, S., ... & Giller, K. E. (2011). Competing use of organic resources, village-level interactions between farm types and climate variability in a communal area of NE Zimbabwe. Agricultural Systems, 104(2), 175-190.

Rusinamhodzi, L., Corbeels, M., & Giller, K. E. (2016). Diversity in crop residue management across an intensification gradient in southern Africa: System dynamics and crop productivity. Field Crops Research, 185, 79-88.

Sanchez, P. A. (2019). Properties and Management of Soils in the Tropics. Cambridge University Press, Cambridge, United Kingdom.

SAS Institute, 2019. JMP Pro 15.0. Cary, North Carolina, USA.

Schmidt, M. W., Torn, M. S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I. A., ... & Trumbore, S. E. (2011). Persistence of soil organic matter as an ecosystem property. Nature, 478(7367), 49-56.

Six, J., Conant, R. T., Paul, E. A., & Paustian, K. (2002). Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant and Soil, 241(2), 155-176.

SoilGrids250m version 2.0; https://soilgrids.org assessed 4 January 2021.

Sokol, N. W., & Bradford, M. A. (2019). Microbial formation of stable soil carbon is more efficient from belowground than aboveground input. Nature Geoscience, 12(1), 46-53.

Sokol, N. W., Kuebbing, S. E., Karlsen-Ayala, E., & Bradford, M. A. (2019). Evidence for the primacy of living root inputs, not root or shoot litter, in forming soil organic carbon. New Phytologist, 221(1), 233-246.

Sommer, R., Paul, B. K., Mukalama, J., & Kihara, J. (2018). Reducing losses but failing to sequester carbon in soils–the case of Conservation Agriculture and Integrated Soil Fertility Management in the humid tropical agro-ecosystem of Western Kenya. Agriculture, Ecosystems & Environment, 254, 82-91.

Soong, J. L., & Cotrufo, M. F. (2015). Annual burning of a tallgrass prairie inhibits C and N cycling in soil, increasing recalcitrant pyrogenic organic matter storage while reducing N availability. Global Change Biology, 21(6), 2321-2333.

Tittonell, P., Vanlauwe, B., Leffelaar, P. A., Shepherd, K. D., & Giller, K. E. (2005). Exploring diversity in soil fertility management of smallholder farms in western Kenya: II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. Agriculture, Ecosystems & Environment, 110(3-4), 166-184.

Turmel, M. S., Speratti, A., Baudron, F., Verhulst, N., & Govaerts, B. (2015). Crop residue management and soil health: A systems analysis. Agricultural Systems, 134, 6-16.

Vanlauwe, B., Gachengo, C., Shepherd, K., Barrios, E., Cadisch, G., & Palm, C. A. (2005). Laboratory validation of a resource quality-based conceptual framework for organic matter management. Soil Science Society of America Journal, 69(4), 1135-1145.

Wander, M. M., & Yang, X. (2000). Influence of tillage on the dynamics of loose-and occluded-particulate and humified organic matter fractions. Soil Biology and Biochemistry, 32(8-9), 1151-1160.

Xu, H., Vandecasteele, B., Zavattaro, L., Sacco, D., Wendland, M., Boeckx, P., ... & Sleutel, S. (2019). Maize root-derived C in soil and the role of physical protection on its relative stability over shoot-derived C. European Journal of Soil Science, 70(5), 935-946.

Yagüe, M. R., Domingo-Olivé, F., Bosch-Serra, À. D., Poch, R. M., & Boixadera, J. (2016). Dairy cattle manure effects on soil quality: porosity, earthworms, aggregates and soil organic carbon fractions. Land Degradation & Development, 27(7), 1753-1762.

Yan, Q., Liu, X., Wang, Y., Li, H., Li, Z., Zhou, L., ... & Bao, X. (2018). Cow manure as a lignocellulosic substrate for fungal cellulase expression and bioethanol production. AMB Express, 8(1), 1-12.

Yang, H. S. (1996). Modelling organic matter mineralization and exploring options for organic matter management in arable farming in Northern China.

Zhu, Y., Merbold, L., Leitner, S., Pelster, D. E., Okoma, S. A., Ngetich, F., ... & Butterbach-Bahl, K. (2020). The effects of climate on decomposition of cattle, sheep and goat manure in Kenyan tropical pastures. Plant and Soil, 451(1), 325-343.

Tables

Table 1: Nutrient content and ^{13}C isotopic signature of maize-based organic inputs and associated nutrient additions used in a mesocosm incubation experiment in western Kenya.

	Organic inputs added				**δ ^{13}C**	**Nutrient additions**		
Organic input	**C**	**N**	**P**	**S**		**N**	**P**	**S**
	------------- % ------------					----- g pot^{-1} ------		
Shoots	52.7	0.79	0.07	0.09	-13.33	0.98	0.27	0.18
Manure	43.3	1.83	0.66	0.17	-13.21	0.48	0.06	0.12
Ex-situ Roots	53.3	0.62	0.10	0.12	-12.44	0.88	0.24	0.16
Control	N/A	N/A	N/A	N/A	N/A	0.98	0.27	0.18

Table 2: Total carbon per soil fraction and whole soil basis, and the carbon to nitrogen ratio of soil organic matter fractions and bulk soil following an 11- month long incubation with maize shoots, roots, and maize-derived cattle manure as well as nutrient additions in a tropical soil in western Kenya. Values presented represent the treatment mean with standard errors presented below each mean in parentheses.

Residue Type	**Nutrient Additions**	**Total C per soil fraction**				**Total C per whole soil**			**Carbon to Nitrogen ratio**			
		fPOM*	**oPOM**	**MAOM**	**Bulk Soil**	**fPOM**	**oPOM**	**MAOM**	**fPOM**	**oPOM**	**MAOM**	**Bulk Soil**
		------------ *g C kg $^{-1}$ soil fraction* --------				--------- *g C kg $^{-1}$ whole soil* --------						
Shoots	No	211	5.41	43.5	29.6	1.12	2.62	21.9	19.4	13.3	12.0	11.6
		(15.4)	(0.255)	(1.68)	(1.64)	(0.16)	(0.18)	(1.12)	(1.24)	(0.47)	(0.04)	(0.23)
Shoots	Yes	204	5.32	45.3	31.1	1.46	2.54	23.1	23.1	13.2	12.1	11.5
		(17.6)	(0.402)	(0.27)	(1.85)	(0.33)	(0.18)	(1.76)	(1.52)	(0.11)	(0.06)	(0.17)
Manure	No	206	4.80	44.9	26.7	1.95	2.69	19.4	19.6	13.0	12.1	11.4
		(18.4)	(0.292)	(0.31)	(1.12)	(0.21)	(0.17)	(0.44)	(1.18)	(0.18)	(0.08)	(0.16)
Manure	Yes	232	5.85	44.7	27.7	1.94	2.97	21.6	20.3	13.0	12.3	11.0
		(20.9)	(0.607)	(0.20)	(1.71)	(0.49)	(0.41)	(1.71)	(1.86)	(0.10)	(0.03)	(0.25)
Roots	No	227	5.54	44.5	28.8	1.70	2.75	22.3	24.1	12.6	12.1	11.8
		(3.8)	(0.311)	(0.35)	(1.26)	(0.20)	(0.31)	(1.63)	(1.55)	(0.81)	(0.04)	(0.09)
Roots	Yes	216	5.09	45.1	30.7	1.86	2.52	22.3	21.1	13.2	12.1	10.9
		(31.4)	(0.115)	(0.37)	(0.79)	(0.27)	(0.16)	(1.39)	(1.57)	(0.33)	(0.13)	(0.22)
Treatment Effects (p-values)												
Residue		*ns*	*ns*	*ns*	*0.092*	*0.064*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
Fertilizer		*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	0.005
Residue x Fertilizer		*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*0.098*	*ns*	*ns*	0.062

*fPOM is free particulate organic matter; oPOM is occluded particulate organic matter, MAOM is mineral-associated organic matter. Numbers show treatments means (n=5) followed by standard error of means in parenthesis.

Table 3: Isotopic values, f values and New Carbon derived from residue additions on a per soil fractions and whole soil basis following an 11-month incubation experiment a using ^{13}C natural abundance approach, with a C4 maize-based residues (shoots, manure, roots) and nutrient additions incorporated into a C3, forest-derived, soil in western Kenya. Values presented represent the treatment mean with standard errors presented below each mean in parentheses.

Residue Type	**Nutrient Additions**	**^{13}C**				**f value**				**New Carbon on a per Soil Fraction Basis**			**New Carbon on a Whole Soil Basis (Proportion of Added C Recovered in Each Fraction)**		
		fPOM*	**oPOM**	**MAOM**	**Bulk Soil**	**fPOM**	**oPOM**	**MAOM**	**Bulk Soil**	**fPOM**	**oPOM**	**MAOM**	**fPOM**	**oPOM**	**MAOM**
		------------------------‰--------------------								g new C kg^{-1} soil fraction g^{-1} C added kg^{-1} whole soil			g new C kg^{-1} whole soil g^{-1} C added kg^{-1} whole soil		
Shoots	No	-23.4 (0.50)	-24.1 (0.07)	-23.7 (0.02)	-23.4 (0.06)	0.169 (0.04)	0.056 (0.006)	0.018 (0.002)	0.030 (0.006)	9.03 (2.04)	0.076 (0.007)	0.198 (0.027)	0.040 (0.014)	0.037 (0.004)	0.099 (0.011)
Shoots	Yes	-20.9 (1.30)	-23.8 (0.06)	-23.7 (0.03)	-23.3 (0.13)	0.364 (0.11)	0.098 (0.005)	0.014 (0.003)	0.045 (0.012)	17.35 (4.60)	0.131 (0.013)	0.157 (0.036)	0.108 (0.025)	0.063 (0.008)	0.084 (0.024)
Manure	No	-22.1 (0.83)	-24.0 (0.08)	-23.7 (0.01)	-23.7 (0.05)	0.267 (0.07)	0.082 (0.007)	0.010 (0.001)	0.006 (0.004)	16.57 (4.77)	0.120 (0.013)	0.135 (0.014)	0.163 (0.054)	0.067 (0.008)	0.058 (0.006)
Manure	Yes	-22.9 (0.47)	-24.0 (0.06)	-23.8 (0.03)	-23.3 (0.17)	0.198 (0.04)	0.070 (0.005)	0.003 (0.001)	0.045 (0.016)	13.33 (1.84)	0.126 (0.016)	0.042 (0.020)	0.111 (0.026)	0.063 (0.008)	0.0.23 (0.013)
Roots	No	-20.9 (0.53)	-23.8 (0.16)	-23.7 (0.05)	-22.9 (0.19)	0.339 (0.04)	0.091 (0.013)	0.011 (0.005)	0.073 (0.017)	19.07 (2.22)	0.127 (0.022)	0.135 (0.036)	0.146 (0.031)	0.063 (0.014)	0.065 (0.018)
Roots	Yes	-21.1 (1.00)	-24.0 (0.21)	-23.8 (0.03)	-23.2 (0.19)	0.320 (0.08)	0.075 (0.017)	0.007 (0.003)	0.050 (0.017)	18.06 (5.31)	0.094 (0.021)	0.082 (0.022)	0.158 (0.052)	0.048 (0.013)	0.042 (0.012)
Treatment Effects (p-values)															
Residue		*ns*	*ns*	*0.013*	*0.019*	*ns*	*ns*	*0.002*	*0.033*	*ns*	*ns*	*0.008*	*ns*	*ns*	*0.011*
Fertilizer		*ns*	*ns*	*0.046*	*ns*	*ns*	*ns*	*0.012*	*ns*	*ns*	*ns*	*0.009*	*ns*	*ns*	*0.068*
Residue x Fertilizer		*ns*	*0.019*	*ns*	*0.078*	*ns*	*0.014*	*ns*	*0.025*	*ns*	*0.044*	*ns*	*ns*	*ns*	*ns*

*fPOM is free organic matter; oPOM is occluded organic matter, MAOM is mineral associated organic matter Numbers show treatments means (n=5) and numbers in parenthesis are standard error of treatment means. NS is treatment differences that are not significantly different at $p<0.05$. f value is the proportion of C from the C4-derived organic residue.

Figure Captions

Figure 1: Fractionation of soil by density and size following an 11-month long incubation of different types of organic input in western Kenya. fPOM is free particulate organic matter, oPOM is occluded particulate organic matter, and MAOM is mineral associated organic matter and SPT is sodium polytungstate. Adapted from Fang et al. (2019).

Figure 2: Impacts of a) residue type and b) nutrient additions on new C stabilized in the mineral-associated organic matter (MAOM) soil fraction following an 11-month incubation experiment, using a ^{13}C natural abundance approach. Maize-based C4 residues (shoots, roots, manure) were incorporated into a C3 forest soil in western Kenya with or without the addition of mineral N, P and S to balance the stoichiometry of the residues. Values represent the mean and error bars reflect the standard error.

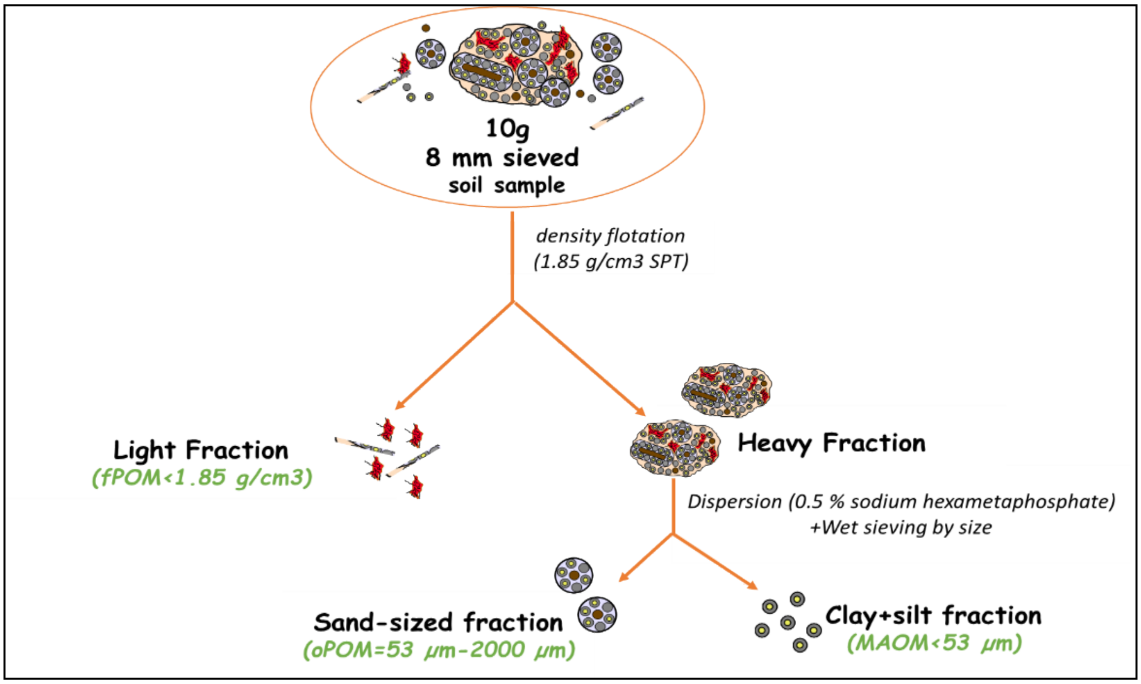

Figure 1: Fractionation of soil by density and size following an 11-month long incubation of different types of organic input in western Kenya. fPOM is free particulate organic matter, oPOM is occluded particulate organic matter, and MAOM is mineral associated organic matter and SPT is sodium polytungstate. Adapted from Fang et al. (2019).

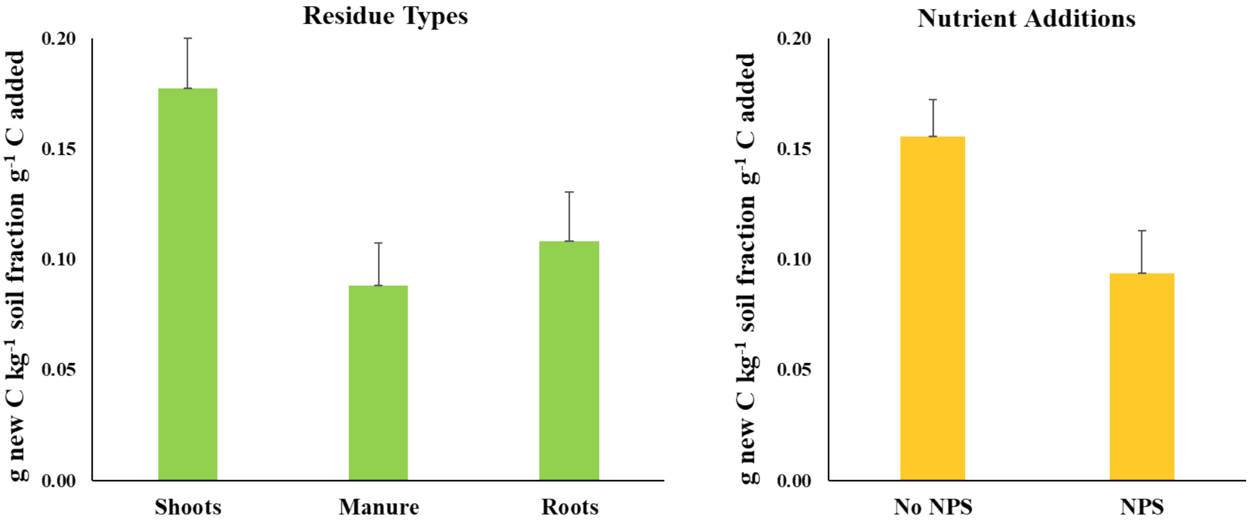

Figure 2: Impacts of a) residue type and b) nutrient additions on new C stabilized in the mineral-associated organic matter (MAOM) soil fraction following an 11-month incubation experiment, using a ^{13}C natural abundance approach. Maize-based C4 residues (shoots, roots, manure) were incorporated into a C3 forest soil in western Kenya with or without the addition of mineral N, P and S to balance the stoichiometry of the residues. Values represent the mean and error bars reflect the standard error.