DISSERTATION

# UNDERSTANDING THE DYNAMICS AND MANAGEMENT OF ORGANIC NUTRIENT SOURCES IN SMALLHOLDER FARMING SYSTEMS: AN INTERDISCIPLINARY APPROACH

Submitted by

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# ABSTRACT

# UNDERSTANDING THE DYNAMICS AND MANAGEMENT OF ORGANIC NUTRIENT SOURCES IN SMALLHOLDER FARMING SYSTEMS: AN INTERDISCIPLINARY APPROACH

Smallholder farmers often face challenges in managing soil fertility due to limited inputs and high spatial variability on their farms. In many places, soil fertility, and overall soil health, is on the decline, and management of organic nutrient sources (ONS) can play a vital role in sustaining the productivity of soils. However, in mixed smallholder crop-livestock systems there is often competition for crop residues between retaining residues within fields versus feeding them to livestock. Understanding how ONS produced on-farm are managed, and the flows and drivers of this essential resource is critical for the restoration and sustainable management of soil fertility and health in smallholder agroecosystems.

The objectives of this study were to: i) validate a soil health tool kit developed to facilitate smallholder research and management involving the use of ONS and other soil management strategies; ii) evaluate how different maize-based ONS (shoot, roots, manure) influence soil organic carbon (SOC) dynamics; iii) understand socio-cultural, economic, and environmental drivers of ONS allocation and use; and iv) understand management and environmental drivers SOC and nutrient (N, P and K) balances across various management scenarios.

To address these objectives, a soil health tool kit to provide in-field quantitative data that are comparable to formal laboratory methods was assembled. I then validated methods used in this tool kit against standard analyses conducted at national laboratories on soils collected from 36

smallholder farms in Kenya and 115 farms in Peru. My results showed that permanganate oxidizable C and pH measured with the tool kit from Kenyan and Peruvian soils were highly correlated to the same variabiles measured by a standard laboratory. The tool kit and standard laboratory measures of available P were less well correlated, but also showed a significant positive relationship. Both tool kit and standard lab analyses displayed similar abilities to predict maize grain yield in Kenya. My findings suggest that the tool kit methods proposed in this study have broad applicability to smallholder farms for explaining variability in crop yields, assessing soil properties of different plots and quantifying management-induced changes in soil health.

In the next study, I used a mesocosm experiment and a $^{13}C$ natural abundance approach, where organic residues (maize shoots, ex-situ maize roots, in-situ maize roots and cattle manure) were incubated for 11 months to trace maize-derived C into different SOC pools. My findings indicated that there was greater stabilization of shoot-derived C (2 X more than manure and 1.6 X more than ex-situ root C) in the mineral-associated organic matter fraction. At the same time, mineral additions of N, P and S (aimed at adjusting the stochiometry of the added residue inputs) led to a 60% decrease in C stabilization in the mineral-associated fraction, compared to a control with no nutrient additions. My study highlights the potential importance of residue retention as a strategy to maintain SOC and therefore soil health and did not support the idea that strategic N, P, and S additions can facilitate C stabilization in soil over the long-term.

I then used focus group discussions and conducted a survey of 184 farming households to understand socio-economic, socio-cultural, and environmental drivers of ONS allocation and use at farm scale in three contrasting agroecological zones of western Kenya. I found that the more resource endowed a farmer is, the more ONS are allocated to the main production plot within a farm. However, beyond resource endowment I observed that agroecological location, and tenure,

perceived soil fertility, gender and social connections also had important influences on ONS allocation.

Lastly, I examined case studies from three representative farm types within three agroecological zones in western Kenya and used a modelling approach to estimate nutrient and C flows in and out of fields. Based on the estimated flows, I then examined different scenarios representing alternative possibilities for ONS management in the region. I noted differences in inputs and allocation between the three zones, but these did not affect the overall balances, which were largely influenced by fertilizer inputs, as well as nutrient export in harvest and soil erosion. Overall nutrient balances were variable, but largely negative across the zones, farm types and field types. When exploring the different management scenarios, reducing erosion led to significantly less negative N balances in all locations. A full residue retention scenario indicated the greatest impact on K balances, while for SOC scenarios with full residue retention and lablab (a high biomass legume) incorporation resulted in at least 50 % more SOC compared to current practices. Scenarios indicate that retaining residues as well as implementing erosion control measures have the potential to effectively reduce nutrient losses as well as improve SOC stocks and that these practices should be encouraged.

As research and development organizations continue to engage with smallholder farmers to reduce the burden of global food insecurity, the insights gained by this research will allow for better anticipation of drivers and obstacles to improved nutrient management in these farming landscapes and communities.

# ACKNOWLEDGMENTS

There is an African proverb that says, “It takes a village (to get virtually everything done)” and indeed this work would not have been possible without the help and support of my “village”. First and foremost, were it not for dedication and thoughtful help of my mentors and advisors Steven J. Fonte and Steven J. Vanek, I would not have been able to enjoy this work. I thank you for believing in me and pushing me to believe in my science. I appreciate the help from my committee Jessica, Michael, and Keith for all the input for this final product and availing yourselves where I required guidance. I appreciate the welcome and assistance I received from our partners, particularly John Ojiem (Multi-purpose Legume Project-KALRO) and Stats4sd. To my loving husband and pillar, Shadreck, I thank you for challenging the norm and choosing to stand by my dreams. You, our boys, and the family weathered not having mummy, daughter and aunty at home months on end. I appreciate your support and love throughout this journey. My friends and trail blazing women in Soil Science, especially my mentor Pauline, I thank you for believing in me and rooting for me.

# DEDICATION

*In loving memory of my mother, I dedicate this work to her for the woman she was.*

*I will forever cherish your love, guidance, mentorship, and support mama.*

*Also dedicated to my angel baby, Xena Paidamoyo; for the woman you would have been.*

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# Chapter 1: Introduction

Smallholder farming communities in sub-Saharan Africa are known to consist of mostly low-input systems and many face issues of declining soil fertility (Bationo et al., 2020). To improve crop production, sustainable intensification approaches seek to optimize the efficacy of organic and inorganic soil inputs (Duncan et al., 2020). This means that farm nutrient cycles and overall farm management must be realigned to ensure adequate crop nutrition and minimize non-productive losses of nutrients. Ultimately, understanding drivers of soil health and nutrient flows in cropping systems is crucial to support long-term productivity and food security.

However, smallholder farmers often face challenges in managing soil fertility due to limited inputs and high spatial variability on their farms, among other factors. Due to this high variability, there is need to have site-specific understanding of soil health status and associated challenges at the plot level and to not rely on regional blanket recommendations, as is often the case (Dass et al., 2014). While this improved knowledge of localized soil constraints could help farmers better manage limited resources more effectively, formal soil analyses are typically out of reach to farmers and small research and development organizations they work with due to the high costs of testing and transport associated with formal analytical laboratories (Nyamasoka-Magonziwa et al., 2020). This highlights the need of low cost, in-field tools to provide quantitative data that are comparable to formal laboratory methods and allow for assessment of soil health parameters considered relevant to farmers. Such parameters include total soil organic carbon (SOC) and associated SOC fractions, pH, aggregate stability, available phosphorus and biological measures. While others have proposed a variety of approaches to measure these indicators, often based on colorimetry, spectroscopy (e.g., Shepherd and Walsh, 2002; Nocita et al., 2015) or sensor technology (Adamchuk et al., 2004), only a small percentage of these tools are being tested in the developing world, especially Africa (Dimkpa et al., 2017). Of the efforts that have focused on Africa and other smallholder contexts (e.g., SoilDoc-Earth Institute, Soil Cares-Wageningen), the technologies may have a place, but are often inaccessible to ordinary farmers and small research organizations or involve highly centralized platforms with databases that are not managed locally.

We therefore assembled a soil tool kit that uses minimal reagents and low-cost equipment to provide in-field quantitative data that are comparable to formal laboratory methods. The second chapter of this dissertation presents validation of the tool kit measurements against standard analyses conducted at national laboratories on soils collected from 36 smallholder farms in Kenya and 115 farms in Peru. The tool kit measurements that were considered include important indicators of soil health (such as permanganate oxidizable carbon (POXC), available P, pH, particulate organic matter (POM), and aggregate stability) that can influence crop yields and multiple soil functions. Additionally, in Kenya, we evaluated two legume treatments, involving the incorporation of residues from: 1) *Lablab purpureus* L. (lablab), versus 2) *Phaseolus vulgaris* L. (common bean) and the ability of the Soil Tool kit to predict yield.

While increased understanding of local soil constraints can help farmers to manage limited soil fertility inputs more effectively, there remains considerable uncertainty regarding which inputs offer the best potential to support SOC accrual and overall soil health. Continuous inputs of organic matter are vital for sustaining the productivity of soils and while multiple organic nutrient sources (ONS) are managed as a key resource by smallholder farmers (Palm et al., 1997; Vanlauwe et al., 2019), their use is often met with challenges. For example, in mixed smallholder crop-livestock systems there is often competition for crop residues between retaining residues within fields versus feeding them to livestock, which can later be returned to the field as manure (Rufino et al., 2007).

Farmer decisions about how to allocate crop residues have important implications for soil health as well as socio-economic outcomes, considering that livestock need to eat and they play important roles in farming households (e.g., for nutrition, food security, investments). In many cases, the decision to retain crop residues or feed them to livestock is not so straightforward. At the same time, root C inputs are an important and reliable input of soil C because they provide a continuous supply of C to soil (i.e., rhizodeposits) during the growing season and typically remain in the soil regardless of decisions made about aboveground residues. Additionally, roots may be preferentially stabilized to increase SOC, more so than aboveground residues or manure (Rasse 2005; Jackson et al., 2017). Despite the importance of these different residue flows and inputs for maintaining soil health and long-term productivity, the dynamics and relative contributions of these different residue types in sustaining SOC remains poorly understood, especially in smallholder farms of the tropics. Along with residue inputs, the use of fertilizers in these systems, while often low, can alter the nutrient stoichiometry of inputs and have important implications for soil C turnover and stabilization (Kirkby et al., 2013), yet great uncertainty persists as to the potential the role of fertilizers and nutrient stoichiometry in regulating SOC turnover.

As such, the third chapter explores how different maize-based inputs that are commonly used by smallholder farmers (roots, shoots and manure) and nutrient stoichiometry (from added fertilizers) contribute to stable SOC pools in smallholder farming contexts of western Kenya. I hypothesized that higher quality litter (i.e., manure) contributes more than maize residues to stable SOC pools. In addition, I hypothesized that root C leads to greater stabilization in all pools than aboveground residues (i.e., maize shoots). Finally, I anticipated that NPS additions, designed to balance the stoichiometry of inputs to reflect the of stable fine fraction of SOC (C:N:P:S-10,000:833:200:143) results in more C stabilization in all pools and all input types. To address these questions, I used a mesocosm experiment and $^{13}C$ natural abundance approach where organic residues (maize shoots, ex-situ maize roots, in-situ maize roots and cattle manure) were incubated for 11 months to trace maize-derived C (with a C4 $^{13}C$ isotopic signature) into different SOC pools within a C3 derived soil from a nearby forest.

Smallholder communities are known to be complex and highly heterogenous, and thus a wide range of factors govern the flow of resources within smallholder farms. Environmental factors (agroecological zone and within-farm soil variability influenced by preferential allocation of ONS to some plots) can affect soil health and management in smallholder systems (Tittonell et al., 2005). Economic resource endowment of farmer households has been shown to be a key driver of nutrient management practices, in smallholder farms because it influences the quantity of organic resources available (Mugwe et al., 2009, Liu et al., 2018). However, beyond farm resource endowment, there are other socio-economic factors such as land tenure, access to local extension and training and socio-cultural variables such as adherence to social norms and interaction with social networks that influence management decisions at the farm level (Leonhardt et al., 2019). Given the interplay of these factors, farmers occupy specific socio-ecological niches and, it is helpful to group farmers/farms that are similar (via typologies or other means) to better understand their utilization of soil fertility practices and management (Alvarez et al 2018). Therefore, an interdisciplinary understanding of the biophysical, socio-economic, and socio-cultural drivers of nutrients, SOC and associated soil management practices in needed to best support soil health and productivity in smallholder communities (see Fig 1.1).

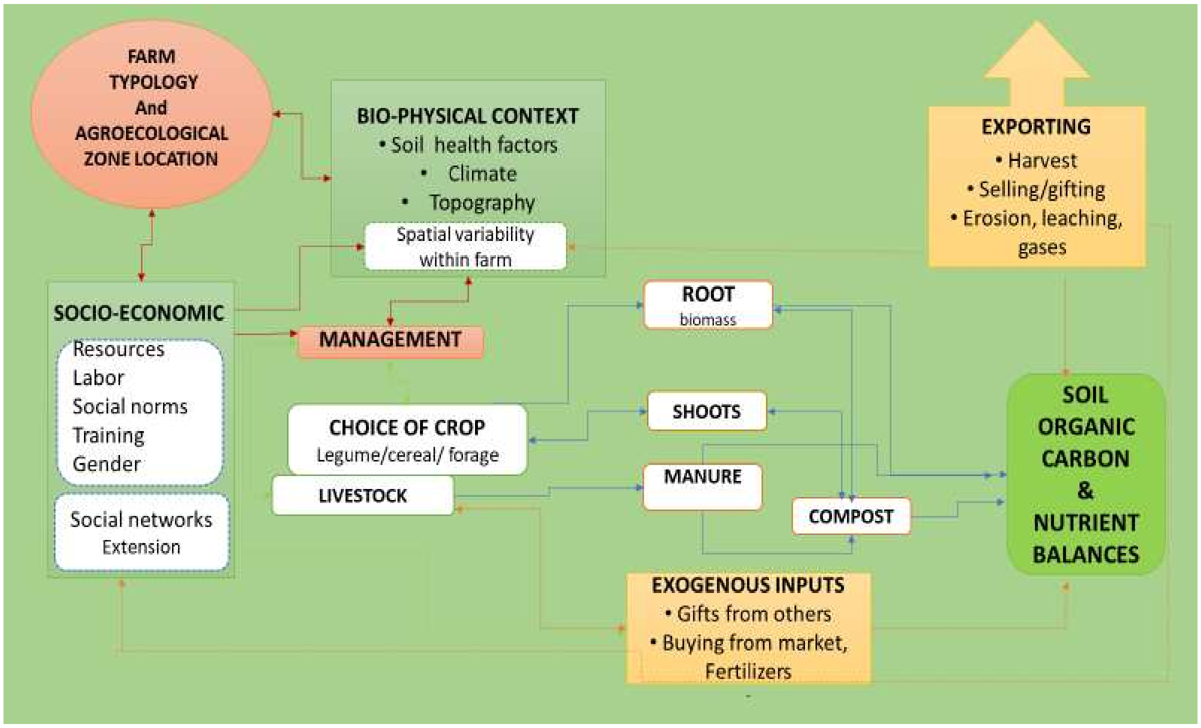

**Figure 1.1**: Conceptual framework for drivers of soil health, organic nutrient sources management and ultimately Soil organic carbon stocks and nutrient balances.

In Chapter 4, I pursue an understanding of how ONS produced on-farm are allocated and what drives farmer decision making around their use. I used focus group discussions and a survey of 184 farming households. I studied socio-economic, socio-cultural, and environmental drivers of ONS allocation and use at farm scales in three contrasting agroecological zones of western Kenya. Specifically, I wanted to understand: i) how ONS are allocated and cycled at farm levels in contrasting agroecological regions, and ii) the dominant socio-economic and socio-cultural factors affecting ONS allocation and cycling for different farm types. I hypothesized that resource endowment together with key socio-cultural variables (e.g. gender, network connections, adherence to social norms, extension, training) and biophysical aspects, such as differences in agroecological contexts (location - which influences climate, soils, and farming systems and perceived soil fertility), are also significant determinants of ONS management. In summary, I hypothesized that these different determinants are expressed as farm types that help to explain different ONS management strategies in the mixed crop-livestock systems of western Kenya.

Nutrient management of organic matter inputs is key to improving crop yields, which are currently around 1 t ha$^{-1}$ maize grain yield (Tittonell and Giller, 2013) in smallholder farming communities in Africa. Therefore, it is crucial to understand the drivers of C and nutrient flows and management and to offer possible strategies to reduce undesirable losses (e.g., due to erosion, leaching and gaseous emissions) and better support long-term soil health and crop production. In order to better manage carbon and nutrient flows in smallholder agroecosystems we need to enhance our understanding of how ONS produced on-farm are allocated and what drives farmer decision making around their use.

I therefore examine N, P and K balances as well as likely trajectories of SOC in smallholder farming communities at plot level and the implications of different scenarios of ONS management on these in the fifth chapter. Two case studies from three representative farm types in each community were selected from three agroecological zones in western Kenya. Using survey data and modelling, nutrient flows in and out of fields for two seasons were estimated to determine overall nutrient balances. Carbon stocks were also modelled for the two seasons using the DayCent model. Five scenarios were compared to business as usual as potential strategies to maintain nutrient balances and stabilize C stocks: 1) reduced erosion, 2) 100% crop retention, 3) feeding all residues to cattle and returning 45% of this biomass as manure, 4) changing from a maize-bean rotation to a maize- high biomass legume (e.g. lablab) rotation and 5) a combination of reduced erosion + high biomass legume + retaining crop residues. Specifically, I sought to: i) evaluate the current N, P, and K nutrient balances and C stocks on a number of representative surveyed farms in in western Kenya, ii) determine the main drivers of nutrient balances and C stocks in western

Kenya, and iii) predict how different management interventions will influence N, P and K balances and C stocks based on four scenarios compared to business-as-usual scenarios drawn from these farms' management information in in western Kenya.

In summary, this dissertation examines the drivers of organic matter management that influence the balance of nutrients and SOC in smallholder agroecosystems, as well as the validation of a soil tool kit that serves as a decision support tool for soil health management.

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# Chapter 2: A Soil Tool Kit to evaluate soil properties and monitor soil health changes in smallholder farming contexts.

## 2.1. Introduction

Agricultural productivity in many smallholder farming systems is limited by inherently low and declining soil fertility. Beyond the more immediate implications for food security and farmer livelihoods, low soil fertility and functionality is likely to exacerbate the effects of climate change in the coming decades (Twomlow et al., 2008, Nelson et al., 2010). At the same time, high spatial heterogeneity of soils complicates management in these systems and often results in sub-optimal yields (Tittonell et al., 2005). While efforts to address soil variability (e.g., the Africa Soil Information System; Leenaars, 2013), have improved our understanding of heterogeneity at multiple scales, local and plot level data remain sparse in most regions, thus limiting our ability to understand and manage for soil properties that drive productivity in smallholder farming communities. Along with improved understanding of soil heterogeneity at the farm scale, farmers and small research organizations would benefit greatly from improved capacity to monitor changes in soil fertility and associated properties over time. New farming practices are often intended to improve soil outcomes but evaluating their effects on soil health and multiple soil parameters is typically beyond the reach of farmers and local researchers. These challenges suggest that improved capacity to assess spatial and temporal variation in key soil parameters offers great promise for advancing the sustainable management of smallholder farm

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Many smallholder farmers and local agricultural research organizations do not adequately consider soil properties in their day-to-day management decisions or on-farm research due to limited access to formal soil analyses. Standard laboratory analyses of soils can be prohibitively expensive due to high service fees as well as shipping costs, especially in more remote areas. Additionally, results are often delayed in reaching the client, thus reducing the utility of this data in many cases (Dimkpa et al., 2017). This suggests a need for local soil analysis options with relatively low cost and quick turnaround time. To address this need, others have proposed a variety of approaches, often based on colorimetry, spectroscopy (e.g., Shepherd and Walsh, 2002; Nocita et al., 2015) or sensor technology (Adamchuk et al., 2004). Despite the development of multiple rapid soil testing options around the world (e.g. Liebig et al., 1996; USDA NRCS,1999; Doran 2002), only a small percentage are being tested in the developing world, especially Africa (Dimkpa et al., 2017). Of the efforts that have focused on Africa and other smallholder contexts (e.g., SoilDoc-Earth Institute, Soil Cares-Wageningen), the technologies certainly have a place, but are often inaccessible to ordinary farmers and small research organizations or involve highly centralized platforms with databases that are not managed locally. Additionally, the methods used by centralized laboratories and platforms are not always shared with local organizations and may even rely on proprietary algorithms - because of this, the results may not be locally understandable and transparent to foster farmer learning about soil health. To address this concern, we assembled a soil tool kit, or set of analyses, that uses relatively few reagents and low-cost materials to provide quantitative results for a range of soil health parameters. The analyses proposed here are designed for use in-field or in ‘near-field’ settings such as regional government or non-governmental organization (NGO) offices, or in farmer-oriented soil health workshops. As such, we seek to provide an entry point for farmer learning about soil health that is linked to their own local knowledge and for more accessible tracking of management impacts on multiple soil properties.

We propose a suite of relatively simple and sensitive soil measures that can be used to improve general recommendations for management of soil fertility and long-term agricultural productivity. These analyses are largely adapted from existing laboratory methods and include pH, aggregate stability, permanganate oxidizable carbon (POXC), available phosphorus (P) and particulate organic matter (POM). The variables considered here offer important insights for understanding soil processes that regulate soil organic matter (SOM) turnover, soil structure, and nutrient availability, all key attributes of soil health and function. For example, phosphorus (P) availability is of interest because it is the most limiting macronutrient in many tropical soils and has been shown to be particularly important for maize production in East Africa and elsewhere (Kihara and Njoronge, 2013; Nziguheba et al., 2016). POXC is thought to represent a labile or recently active soil C fraction that is sensitive to environmental management, but also reflects trends in total soil C (Weil et al., 2003; Culman et al., 2012). Given that the analyses presented here represent an adaptation of standard lab measures for use in more remote settings, it is important to validate these analyses against those done in standard labs tests. It should also be noted that this is a preliminary, core set of measures that we are actively building upon to expand the utility of our tool kit (see www.smallholder-sha.org).

We sought to evaluate the performance of our tool kit within the context of participatory on-farm cropping systems trials in Kenya and Peru. In these systems, the inclusion of multi-purpose legumes in cropping rotations has been proposed to improve soil nutrient and carbon balances and overall soil health (Ojiem et al., 2014). Specifically in Kenya, a previously established field experiment sought to understand the impact of including *Lablab purpureus* (vs. other legumes) in rotation with maize, as this legume has a wide range of uses including forage and soil fertility improvement, due to its ability to fix nitrogen (N) and produce considerable biomass (Pengelly and Maass, 2001). The tool kit was applied in this trial as well as in characterizing on-farm trial sites to examine improved fallow options in the highlands of Peru. In both Kenya and Peru, tool kit analyses were validated against results from a reputable laboratory in each country.

The objectives of this study where therefore to: i) validate our tool kit analyses vs. standard laboratory methods across diverse soil types in Kenya and Peru. Then, in Kenya, we also aimed to: ii) test the ability of our tool kit measurements to detect rotation treatment effects on soil properties from increased legume biomass input from *L. purpureus (*lablab*)* vs. *Phaseolus vulgaris (*common bean*)*, and iii) explore the potential for the measured soil properties to predict maize yield and compare this with standard laboratory measurements. It was hypothesized that measurements of POXC, available P, and pH obtained with our tool kit are highly correlated with results from standard laboratory methods. We also hypothesized that the incorporation of *lablab* residues in maize cropping systems would result in residual soil fertility improvements that we would be able to detect with tool kit analyses. Finally, we hypothesized that both our soil tool kit and standard laboratory methods would be able to explain variability in grain yield to a similar degree.

## 2.2 METHODOLOGY

### 2.2.1 Study site and experimental design in Kenya

Sampling was conducted in Nandi County in western Kenya at sites between 1300 and 1900 m in elevation roughly between latitudes 0.0° to 0.2°N and 34.8° to 35.2°E (Fig. 2.1a). Mean annual rainfall is around 1700 mm, with a bimodal distribution, where long rains occur from

February to July and short rains occur between September and November. The mean annual temperature is 20˚C with average monthly temperatures ranging from 12 ˚C in July to 25 ˚C in March. Soils in this area are mainly Oxisols (USDA classification system; Soil Survey Staff, 2014) or Ferralsols (FAO classification system; FAO, 1988). In general, they are highly weathered, have a low pH and base saturation, low cation exchange capacity (CEC) and high content of sesquioxides (Landon, 2014).

In March of 2015 a set of on-farm experiments was established across 36 smallholder farms to examine the effect of different legume species (and incorporated residues) on the growth and performance of maize (*Zea mays L*) for multiple growing seasons (Table 2.1). The legumes, lablab or beans, were grown during the short rainy season and the residues were then incorporated into the soil to a depth of 15 cm using a hand hoe following grain harvest. The biomass incorporated into the soil was on average estimated to be 7.0 Mg ha$^{-1}$ of lablab compared to 0.7 Mg ha$^{-1}$ for bean. Both treatments were randomly assigned to plots (4 x 4 m) in each field on all 36 replicate farms. Maize was then grown on these plots during three successive cropping cycles (two long rains and one intervening short rain season over two years) before sampling to assess the combined impact of both legume incorporation and subsequent maize cropping.

**Table 2.1:** Agronomic management of maize-legume integration field trials established in farmers' fields in Nandi County, Kenya in 2015. Trials established by Kenya Agricultural and Livestock Research Organisation (KALRO), based in Kibos, Kenya

| Season | Crop | Planting density (Seeds ha$^{-1}$) | Fertilization | Tillage |
|---|---|---|---|---|
| Short 2015 | Legume treatments | *P. vulgaris* = 22 500 or<br>*L. purpureus* = 7 312 | Triple Super phosphate (TSP) 30 kg ha$^{-1}$ | Hand hoe |
| Long 2016 | Maize | 40 000 | none | Hand hoe |
| Short 2016 | Maize | 40 000 | none | Hand hoe |
| Long 2017 | Maize | 40 000 | none | Hand hoe |

Short = short rainy season (October to December), Long = long rainy season (April to July).

### 2.2.2 Soil sampling and preparation in Kenya

Soil samples were collected at the time of maize harvest in the 2017 long rains season (24 months after legume incorporation). In each treatment plot, eight sub-samples were taken to a depth of 20 cm using a soil auger (3 cm diameter) and combined into one composite sample. From the same plots, two relatively less-disturbed core samples (0-5 cm depth) were taken using a metal cylinder (4.5 cm diameter) gently inserted into the soil surface for determination of bulk density and aggregate stability. The cylinders were carefully excavated and trimmed with a knife and the soil emptied into a sealed plastic bag, where they were kept cool and undisturbed until further processing in the lab.

Upon return to the lab, the 0-20 cm samples were air-dried, sieved to 2 mm and stored for subsequent analysis of pH, POXC, available P, and POM (see methods below). The 0-5 cm cores were weighed, and a sub-sample of the core was dried at 105 °C for determination of moisture content and bulk density. The rest of the field-moist soil from each plot was combined to form one composite sample per plot and passed through an 8 mm sieve by gently breaking soil clods along natural planes of weakness. This material was then air-dried for determination of aggregate stability (see method below).

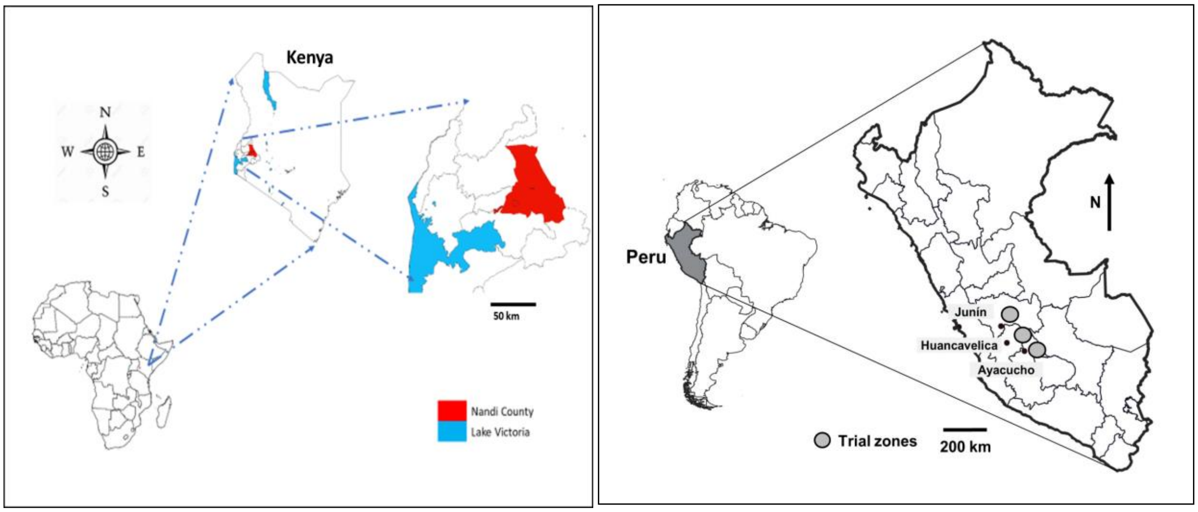

**Figure 2.1:** Maps showing the study site location in Nandi County, Western Kenya (top) and trial zones of experiments in the Andes of Peru, in the regions of Junín, Huancavelica, and Ayacucho (bottom).

### 2.2.3 Study Sites and Sampling in Peru

One hundred and fifteen production fields in the Peruvian regions of Junín, Huancavelica and Ayacucho (Fig. 1.1b) were sampled in September 2017 prior to installation of a multi-year experiment testing options for forage-based fallows with mixtures of annual and perennial legumes. These sites lie between latitudes 11.8 °S and 13.4 °S and longitudes 73.8° W and 75.3° W and range in elevation from 3100 to 4200 m. Soils at the sites are mostly developed on hillsides from sedimentary parent materials and are principally haplic to dystric cambisols and kastanozems, as well as some andosols in the Ayacucho region where outcrops of volcanic rock occur (World Reference Base mapping from www.soilgrids.org); USDA equivalent types for the sites are Orthents, Ustolls, and Ustalfs. The mean annual temperature is 12˚C with a range of monthly mean temperatures between 7 ˚C in July and 16 ˚C in December. Average precipitation ranges from 730 to 950 mm, mainly occurring between October and May (www.worldclim.org). Eight subsamples per field were taken using a soil corer (2.5 cm diameter) to a depth of 20 cm and combined into a single composite sample. Soil was then air-dried, sieved to 2 mm, and analyzed as described below.

We note that samples were not collected for soil structural attributes (bulk density and aggregate stability) in Peru due to logistical constraints and the fact that these are not standard available tests offered in the national lab.

### 2.2.4 Tool kit measurements

For soils collected in both Kenya and Peru, pH was measured in a 2:1 deionised water: soil suspension. The mixture was stirred for 1 min and left to settle for 20 minutes swirling occasionally and pH was then measured using a low-cost portable pH meter - Extech model PH110 (Extech, Waltham, MA, USA).

Evaluation of POXC employed a method adapted from Weil et al. (2003) that is based on the oxidation of labile soil organic C by potassium permanganate ($KMnO_4$). A 2.5 g soil sample was mixed with 20 mL digestion solution (0.015 M $KMnO_4$ and 0.1 M $CaCl_2$). The mixture was shaken by hand for 2 min and left to settle for 10 min. Then, 0.5 mL of the supernatant was added to 30 mL deionised water in a centrifuge tube. This solution was placed in a vial and absorbance read with a field colorimeter (Hanna model HI-717 phosphate high range colorimeter, Hanna instruments corp., Woonsocket, RI USA). The absorbance of a 100% $KMnO_4$ blank solution (without soil addition and diluted in the exact same way as the sample solution) was used as a control. The POXC concentration was then calculated using the following equation:

$$\text{POXC} = (1 - \text{CR} / \text{Blank}_{\text{CR}}) * \text{M} * \text{V} * 9000 / \text{m} \qquad (2.1)$$

where POXC is potassium permanganate oxidizable carbon in mg C $kg^{-1}$; CR is the sample colorimeter reading (arbitrary units based on absorbance at 525 nm), $\text{Blank}_{\text{CR}}$ is the reading of the blank 100% permanganate solution in the same units; M is Molarity of the $KMnO_4$ (0.015 M), V is Volume (0.020 L), 9000 is a conversion factor used to convert moles $KMnO_4$ consumed to mg of active C in soil oxidized by the $KMnO_4$, and m is the mass of the soil used (Weil et al., 2003).

Available P was determined using a modified Olsen method (Olsen, 1954). A sub-sample, 2.5 g, of air-dried soil was placed in a container along with 25 mL Olsen solution (i.e., 0.5 M $NaHCO_3$, adjusted to pH 8.5 using NaOH). The mixture was shaken for 20 min and then left to settle for 10 min. A pre-wet filter (Whatman's qualitative # 5 grade with nominal pore size of 2.5 µm) was then used to collect a filtrate free of suspended clays. The filtrate was analysed for reactive P using the ascorbic acid / molybdate blue method for Olsen soil extracts with a protocol adapted to the field colorimeter, as follows: 10 mL filtrate was added to 0.6 g dry $NaHSO_4$ to neutralize the Olsen extract and allow release of $CO_2$ gas from the bicarbonate solution, until significant bubbling stopped, and the pH was below 6, to allow further acidification and analysis using the ascorbic acid method. Then in a graduated cylinder, the neutralized filtrate was added and diluted up to 20 mL with deionized water. The 20 mL solution was then transferred into two vials, one with the phosphate reagents for the ascorbic acid / molybdate blue method for reactive P (Hanna HI-93713 reagent pack, Hanna Instruments, Woonsocket, RI, USA) and the other without, i.e. a blank with the original light-brown color from the soil extraction. The vial with reagent added was left to develop a blue color for 15 min and the concentration of P was noted from the colorimeter using the vial without reagent added as a color blank for the generally slightly yellow-brown color of the Olsen extract. The inorganic P concentration in solution was then calculated as follows:

$$P_{inorg} = \frac{(Df * (0.1459 * CR) - 0.0925) / 2.23 * V}{m} \qquad (2.2)$$

where $P_{inorg}$ is the inorganic P in the sample in mg $kg^{-1}$ ; Df is the dilution factor from 10 mL to 20 mL = 2; 2.23 is the conversion between phosphate ($P_2O_5$) and elemental mass of P; 0.1459 and 0.0925 are obtained from a calibration curve made by analysing Olsen solutions with known concentrations of added phosphate; CR is the colorimeter reading in nm; V is the volume of Olsen solution used to extract the soil = 0.025 L; m is the mass of soil analyzed =0.0025 kg.

For Kenyan samples, POM was determined using density flotation with deionized water. In brief, 70 g air-dried soil was placed on a 2 mm sieve in a small basin. The sieve and soil were then submerged, and the soil was left to soak for 10-20 s for slaking. The sieve was then lifted in and out of the water gently, and some gentle additional pressure was applied with fingers to disrupt aggregates on the sieve to liberate organic matter. All the material passing the 2 mm sieve was then transferred to a 250 µm sieve to capture coarse sand and POM between 250 µm and 2000 µm in size. Material that did not pass through the 250 µm sieve was then rinsed into a beaker and decanted into a basin with POM suspended in water (specific gravity ~ 1.0) separated from denser particles at the bottom of the beaker. The process of decantation was continued until the suspension was clear of floating POM. Since no clay dispersal agent was used, we replaced its function by gently breaking apart larger aggregates by hand on the sieve as described above, checking that after decanting water in the beaker was free of suspended clays, and that the remaining settled sand particles from decanting consisted of clean mineral sand. POM was then trapped on a 250 µm sieve and transferred to a pre-weighed foil cup using a rinse bottle. The POM was then dried at 60°C and weighed on a microbalance with precision of 0.1 mg.

Aggregate stability was determined on Kenyan samples using methods adapted from Elliott (1986). A 50 g subsample of air-dried, 8 mm sieved soil was placed on top of 2 mm sieve in a small basin and water added until the soil was submerged (~1 cm above the sieve). The soil was left for 2 min for slaking and then wet-sieved by moving the sieve in and out of the water 50 times during a 2 min period. Soil remaining on the 2 mm sieve was then rinsed into a pre-weighed aluminium tin using a rinse bottle. Material that had passed through the sieve was transferred to a

250 µm sieve and the process was repeated to obtain two water stable aggregate fractions: large macroaggregates (> 2000 µm) and small macroaggregates (250–2000 µm). Both fractions were then dried in an oven at 105ºC and the mass of soil passing through the 250 µm sieve was determined by difference. Mean weight diameter of the aggregate size classes was calculated out of the total initial weight of 50 g dry soil according to methods by Van Bavel (1950).

### 2.2.5 Laboratory analysis for tool kit validation

In Kenya, the 0-20 cm soil samples were also analysed by Crop Nutrition Laboratory Services Ltd. (Nairobi, Kenya) for parameters including soil pH (2:1 water: soil) and Mehlich-III available nutrients (Mehlich, 1984), as this was the recommended local test to assess the availability of cation nutrients as well as P in soils. The Mehlich-III extracted nutrients were determined using inductively coupled plasma optical emission spectroscopy (ICP-OES). POXC was measured according to similar methods to our field method for POXC, but in a lab setting (Weil et al., 2003). Soil total C for Kenyan sites was analyzed at the World Agroforesty Centre in Nairobi, Kenya using dry combustion (Nelson and Sommers, 1982) of 15-20 mg sample of ground soil on a Thermo-Fisher organic elemental analyser model FLASH 200 series (Thermo Fisher Scientific, South Africa). In Peru, the samples were analysed at the La Molina National Agricultural University laboratory (Lima, Peru) for pH (1:1 water:soil), available phosphorus (Olsen extraction and ascorbic acid colorimetric method), organic matter (loss on ignition) and POXC (Weil et al., 2003). Soil organic carbon was estimated for the Peru sites multiplying the organic matter content by a conversion factor of 0.58.

### 2.2.6 Grain yield

Maize grain yield for the experiment in Kenya was determined by harvesting the whole plot separately for each treatment, weighing the dry maize grain, and dividing by the plot area. A sub-sample of the grain was weighed for determination of moisture using a moisture meter and actual yield was calculated by adjusting the measured yield to 13% grain moisture content.

### 2.2.7 Statistical analysis

All statistical analyses were conducted using R version 3.4.3 (R Core Team, 2017). Simple linear regression was used to assess bi-variate correlations between the tool kit results vs. traditional laboratory methods for both Kenya and Peru data separately. For Kenya soils, simple linear regression was also used to examine correlations between individual soil parameters and maize grain yield, based on the two long rainy seasons. Yield from the short rainy season was left out because of partial crop failure associated with low rainfall and the maize necrotic virus. Paired t-tests, considering paired treatments of lablab versus bean residue incorporation on each farm, were conducted to assess treatment effects on soil parameters across all farms.

In order to better understand the utility of our tool kit vs. standard laboratory methods, we used a model selection approach to explore which soil properties measured from Kenya samples best predict grain yield. Two multiple linear regression models, one for each soil analysis platform (soil tool kit and laboratory soil data) were fit to grain yield data using the lm () function from the ‘car’ package in R (Fox and Weisberg, 2011). The mean grain yield of the two long rainy seasons was the response variable, while legume residue treatment was included in all models along with soil analysis predictors from the two data sources. We used the Akaike Information criteria (AIC) to compare different models and the “best model” was determined using the smallest AIC value (Akaike, 1987; Burnham and Anderson, 2004). Selection was based on all subsets' selection with the dredge () command from the MuMIn package in R (Barton, 2018). Multilinear regressions were run on the selected models to get the summary for each final model. Data for regressions and ANOVA were checked for adherence to model assumptions (e.g., using residual plots vs fitted values for homogeneity of variance, normal Q-Q plot for normality of residuals) and ln transformed as needed. Additionally, we examined outliers using Cook's distance, considering all values greater than 0.5 as potential outliers; however, no outliers were removed based on this criterion.

## 2.3. Results

### 2.3.1 Comparison of tool kit vs. lab measured soil properties

For Kenya soils, soil tool kit measured pH and lab measured pH were positively correlated ($p<0.001$; $R^2=0.55$; Fig. 2.2a). There was also a significant correlation between tool kit available P and ln(Mehlich P) from the lab ($p<0.001$; $R^2=0.30$, Fig. 2.2b), although some very high values of Mehlich P reduced the level of correlation between the Mehlich III and the tool kit Olsen-based measures. Tool kit measured POXC was highly correlated with both lab measured POXC and total C ($R^2=0.77$ and $R^2=0.72$, respectively; Fig. 2.2c and d).

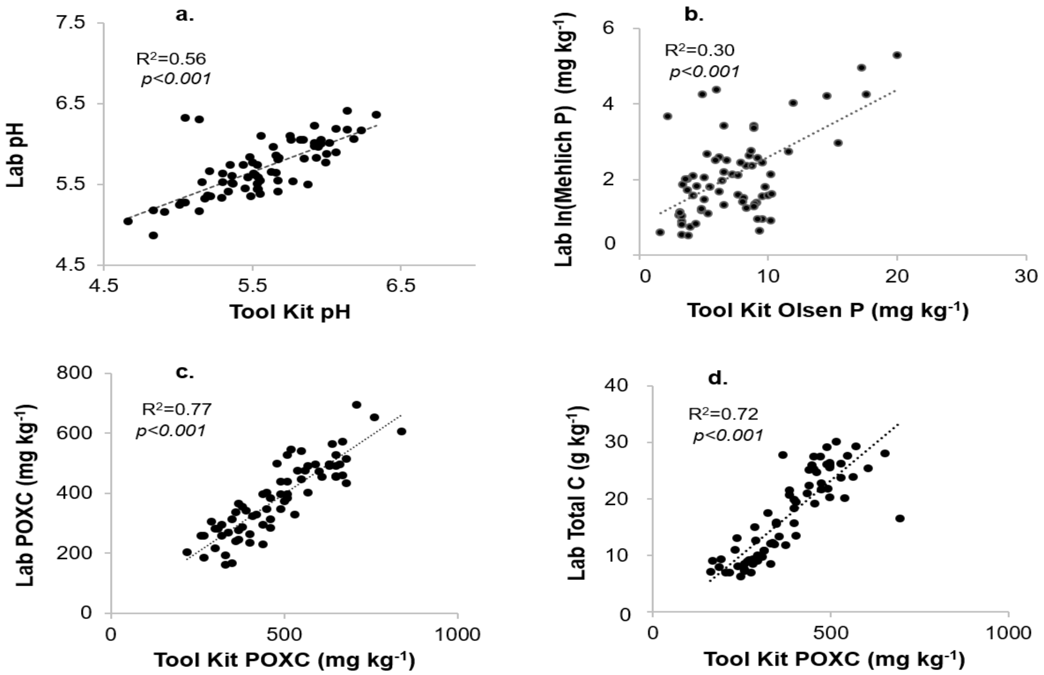

**Figure 2.2**: Relationships between the soil kit vs. standard lab methods for Kenyan soils (n = 72): a) tool kit soil pH vs. lab pH; b) tool kit available P (Olsen method) vs. ln (lab available P) via the Mehlich-III method; c) tool kit permanganate oxidizable C (POXC) vs. lab POXC; and d) tool kit POXC vs. lab total soil C measured via dry combustion. Soil samples were collected in July 2017, 3 seasons (24 mo.) after incorporation of legume residues (*P. vulgaris* or *L. purpureus*) in an Oxisol soil of Nandi County, Kenya.

For Peruvian soils, similar validation results were noted. Tool kit measured pH and lab pH were strongly and positively correlated ($p<0.001$; $R^2=0.69$; Fig. 2.3a). There was also a significant correlation between available P measured by our tool kit vs. the lab result ($p<0.001$; $R^2=0.35$, Fig. 2.3b), with both analyses using the Olsen extraction for plant-available P. Tool kit measured POXC was highly correlated with both lab-measured POXC and estimated SOC based on SOM using loss on ignition ($R^2=0.75$ and $R^2=0.62$, respectively; $p< 0.001$; Fig. 2.3c and 2.3 d), which also aligned with the POXC vs. total C validation results from Kenya. Despite the high degree of correlation, estimates of both POXC and available P were both higher overall for the university lab-based results in Peru. The POXC results from the university lab were 40 to 50% higher than tool kit results on the same sample, while the Olsen P results from the university lab were on average 60%

higher than with the tool kit, in part due to larger scatter and some very high values in the university lab results, which was the same pattern seen in the Kenyan lab results.

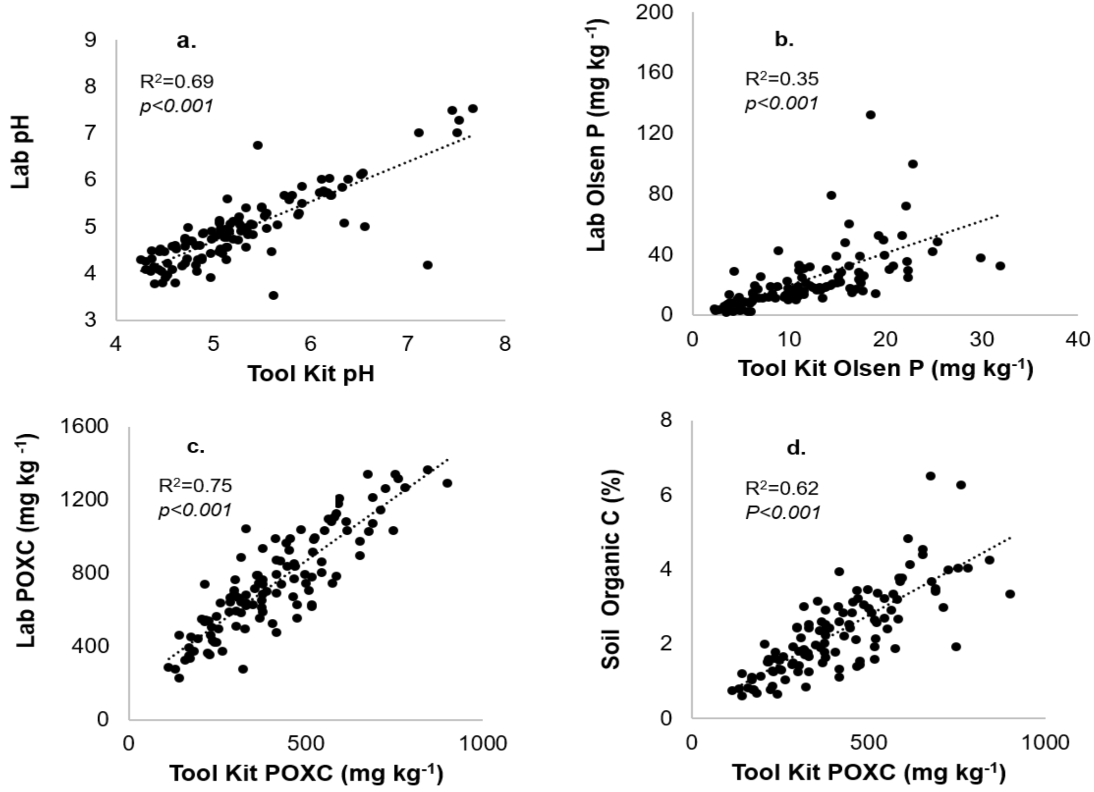

**Figure 2.3:** Relationships between the soil tool kit vs. standard wet chemistry methods for Peruvian soils (n=115): a) Tool kit soil pH vs. lab assessed soil pH b) Tool kit available P (Olsen method) vs lab available P (Olsen method); c) Tool kit permanganate oxidizable C (POXC) vs. lab POXC; and d) Tool kit POXC vs. lab total organic soil C based on organic matter measured by loss on ignition. Soil samples were collected during September 2017 from a variety of mountain soils in experiment sites of central Peru.

### 2.3.2 Tool kit evaluation of soil health changes

In assessing soil properties in Kenya 24 mo. after incorporating either *L. purpureus* or *P. vulgaris* residues, significant treatment effects were only observed for POM, such that POM was 33% higher in plots that were previously under *L. purpureus* (Table 2.2). Additionally, while not significantly different, we note that soil parameters evaluated by the tool kit in the lablab treatment were generally higher than plots with common bean for most of the properties compared, such as POXC, available P, and aggregate stability (Table 2.2).

**Table 2.2:** Mean values for soil properties under two legume treatments: growth and incorporation 1) *P. vulgaris* or 2) *L. purpureus* residues. Sampling was conducted in Nandi, Kenya in June 2017, three seasons (24 mo.) after legume incorporation.

| **Method** | **Soil property** | **Treatment** | | |
|---|---|---|---|---|
| | | ***P. vulgaris* residues *(n=36)*** <br> *Mean±SE* | ***L. purpureus* residues *(n=36)*** <br> *Mean±SE* | ***p value*** |
| **Soil Tool Kit analyses** | pH | 5.54 ± 0.06 | 5.50 ± 0.06 | *0.366* |
| | Olsen P (mg P kg $^{-1)}$ | 7.28 ± 0.59 | 7.39 ± 0.64 | *0.766* |
| | POXC (mg C kg $^{-1}$) | 379 ± 21 | 384 ± 19 | *0.500* |
| | POM (mg g$^{-1}$) | 1.2 ± 0.1 | 1.6 ± 0.12 | *0.007*** |
| | Bulk Density (g cm$^{-3}$) | 1.31 ± 0.03 | 1.31 ± 0.03 | *0.811* |
| | MWD (µm) | 660 ± 10 | 680 ± 20 | *0.754* |
| **Laboratory analyses** | pH | 5.69 ± 0.06 | 5.71 ± 0.06 | *0.557* |
| | Mehlich P (mg P kg $^{-1}$) | 19.16 ± 5.6 | 20.77 ± 6.38 | *0.453* |
| | POXC (mg C kg $^{-1}$) | 483 ± 23 | 469 ± 26 | *0.344* |
| | Total Nitrogen (g kg$^{-1}$) | 1.59 ± 0.12 | 1.64 ± 1.22 | *0.241* |
| | Total C (g kg$^{-1}$) | 16.89 ± 1.29 | 17.27 ± 1.25 | *0.491* |

** are treatment means that are significantly different at p value <0.05 using paired t-tests comparison. P is phosphorus, POM is particulate organic matter, MWD is aggregate mean weighted diameter and SE is standard error of means.

### 2.3.3 Ability of measured variables to explain variability in grain yield

Variables measured by the tool kit were compared to those from standard lab for their ability to explain variability in maize grain yield (average over two long growing seasons) following *P. vulgaris* or *L. purpureus* residue incorporation (Fig. 2.4). In examining bivariate correlations between yield and soil predictors, significant positive correlations with yield were found for tool kit Olsen P ($p<0.001$; $R^2=0.28$) and lab ln(Mehlich P); $p=0.023$; $R^2=0.10$ as well as for both POXC measured with the tool kit ($p<0.01$; $R^2=0.20$) and the laboratory methods ($p<0.001$; $R^2=0.23$).

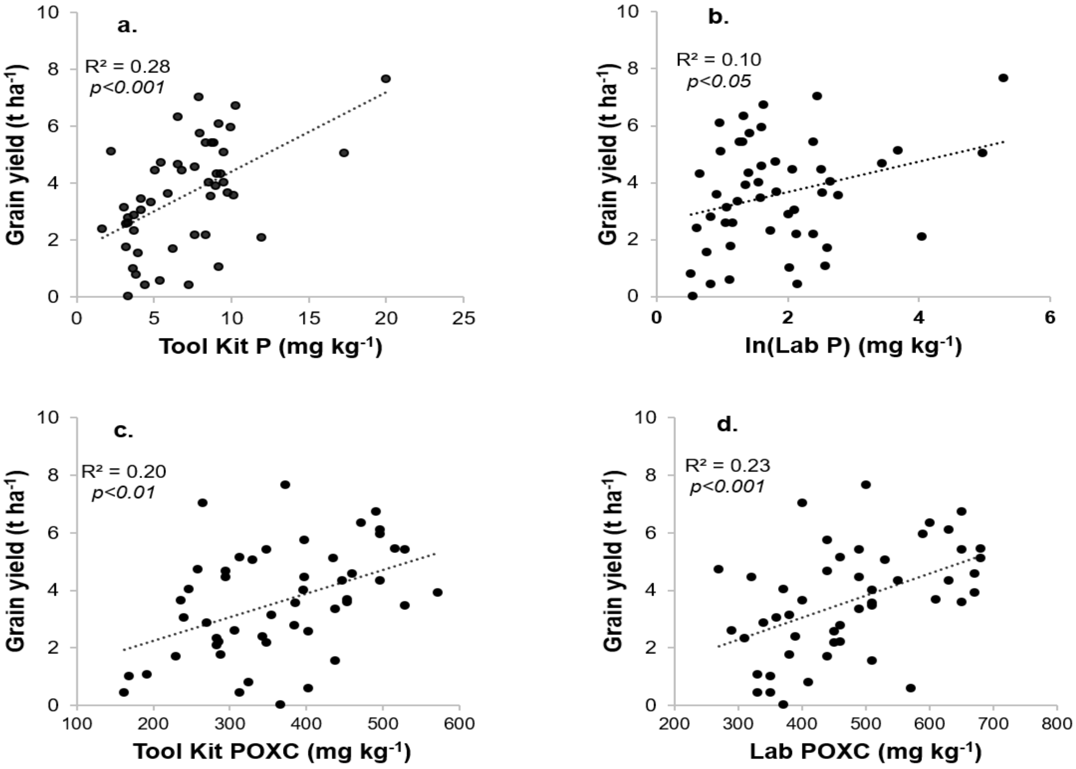

**Figure 2.4:** Maize grain yield (averaged over 2 long seasons) as explained by bivariate regressions with a) Tool kit soil available phosphorus (Olsen P); b) lab measured soil available P (Mehlich-III P); c) Tool kit soil permanganate oxidizable carbon (POXC); d) lab measured POXC. Soil data shown is from samples taken subsequent to maize cropping during the two years after incorporation of legume residues of *P. vulgaris* and *L. purpureus* in an Oxisol in Nandi, Kenya

The models selected for tool kit vs. laboratory variables to predict yield had very similar AIC values (AIC = 171.4 for soil tool kit; AIC=173.3 for laboratory methods) and adjusted $R^2$ values (soil tool kit $p<0.001$, $R^2 = 0.55$; lab $p<0.001$, $R^2 = 0.53$; Table 2.3). Both models have reasonably small root mean squared error (RMSE) values (1.255 for the tool kit; 1.291 for the laboratory methods). For the tool kit selected model, 59% of variability in maize grain yield is explained by the linear regression with treatment, pH, POXC and Olsen P terms, while for the laboratory methods, 55% of variability in maize grain yield is explained by the linear regression with treatment, POXC and Mehlich P terms.

**Table 2.3:** Final selected regression models based on Akaike information criterion (AIC) selection using data from the soil tool kit and standard laboratory methods to explain maize grain yield. Sampling was conducted in Nandi, Kenya in June 2017, three seasons (24 mo.) after legume incorporation. Models were based on the AIC to select each final model. RMSE is the root mean squared error.

| Model | | $R^2$ | Adjusted $R^2$ | RMSE | AIC | p value |
|---|---|---|---|---|---|---|
| **Soil Tool kit** | | | | | | |
| Model terms | | | | | | |
| Predictor | p value | | | | | |
| Treatment | <0.001 | | | | | |
| pH | 0.143[ƚ] | 0.589 | **0.553** | 1.255 | 171.4 | <0.001 |
| POXC | <0.01 | | | | | |
| Olsen phosphorus | <0.001 | | | | | |
| **Laboratory** | | | | | | |
| Model terms | | | | | | |
| Predictor | p value | | | | | |
| Treatment | <0.001 | | | | | |
| pH | [δ] | 0.557 | **0.523** | 1.291 | 173.3 | <0.001 |
| POXC | <0.001 | | | | | |
| Mehlich phosphorus | <0.01 | | | | | |

[ƚ] variable was selected for the final model, but was not significant.

[δ] model term was not included in the final model during AIC all subsets selection.

## 2.4. Discussion

Our findings suggest that the tool kit analyses proposed here offer a relatively robust set of measures across diverse smallholder contexts and have considerable potential to support research and guide soil management decisions for improved soil health.

### 2.4.1 Comparison between tool kit and lab measured parameters

The simplified POXC analysis in our tool kit offers a comparatively rapid and low cost means of evaluating a labile or recently active SOC pool that has been shown to be sensitive to management (e.g. Bongiorno et al. 2019). In support of this, a study carried out by Culman et al. (2012), POXC showed a higher sensitivity to management changes than other labile C pools across a range of sites. Our tool kit measured POXC also demonstrated a strong correlation with the lab measured POXC as well as total C. This finding agrees with Tirol-Padre and Ladha (2004) who reported total C to be highly correlated to POXC, meaning that it can provide a proxy measure for changes in SOM. This is important since, although SOM is a critical indicator of soil health, it is usually more expensive to measure. While we did not find an impact on POXC with different legume treatments, this was not entirely surprising given that these treatments were not so different, with just one crop substitution (lablab vs. bean) three seasons prior to evaluation. However, the significant correlation between maize grain yields and POXC for the Kenyan soils, suggests promise in the use of tool kit measured POXC for providing an indicator of overall soil fertility.

Soil pH is an important indicator of fertility in tropical soils, as it has implications for crop root development and nutrient availability (Osundwa et al., 2013). In this study, the sites varied in soil pH from highly acidic to neutral across the two country contexts (Figures 2.2a and 2.3a). We note that the tool kit battery-operated pH meter performed well compared to laboratory pH measurements, making it a good alternative in remote areas with unreliable electricity. Given that soil pH is important for plant growth and choice of crop, easy access to pH measurements via the tool kit could help support smallholder farmers in making better management decisions.

The Olsen extraction for P was selected for our tool kit because it requires relatively few and more easily accessible reagents than other methods in common use around the world, such as the Mehlich or Bray P tests. Overall, we note that the test performed well across farms in both Kenya and Peru, as our tool kit P was significantly correlated with standard lab data and was a valuable predictor of maize yield. Although Olsen P has traditionally been considered as best adapted for neutral and alkaline soils, the positive correlation we found between Olsen P and Mehlich-III P in the Kenya samples broadly agrees with the findings of Khan et al. (2018) and also Farina and Channon (1979) who demonstrated that the Olsen P performed just as well as other extraction methods in acidic soils. Dabin (1980) proposed a modified Olsen extractant with the addition of ammonium fluoride but noted the general appropriateness of the Olsen test to soils with aluminum- and iron-associated P. Fixen and Grove (1990) noted that the relative adequacy of Olsen P across a wide range of soil pH may be due to the fact that bicarbonate ions can desorb P from both calcium and iron oxide sorption sites in soils. They also cited a number of studies showing correlation r values greater than 0.85 between Olsen and different Mehlich methods in soil sets including acidic soils down to pH 4 (Fixen and Grove 1990). In practice, for organizations seeking an easy to perform test for P status of soils, our study shows that Olsen P provides a valuable metric with reasonable accuracy, using reagents and equipment that are relatively easy to acquire compared to other tests, especially given the ability to explain variability in maize yield across the Kenyan smallholder sites. However, it bears noting that our validation set of soils did not adequately represent andosols with very high levels of P sorption, which are known to present difficulties not just for the Olsen test but also for other chemical extraction methods (Fixen and Grove 1990; Sugito and Shinano 2013), and the use of our simplified Olsen method needs to be further validated in such soils.

Additionally, the overall higher available P from laboratory Olsen P analyses in Peru (Fig. 3b) suggest that there still may be variation among organizations and regions carrying out the test. In the case of our Peru samples, we suspect that different ambient air-drying temperatures between the mountain climate where the tool kit tests were performed (at ~3100 m) and the warmer climate in Lima (at ~ 50m) may be, at least in part, responsible for this result. We note that many of these samples had relatively high organic matter content (Fig. 2.3d) and that additional mineralization of SOM may have occurred during transport and storage of samples in Lima before the laboratory analyses, thus increasing the lab levels of Olsen P and POXC. A similar finding was reported with drying of Irish peat soils by Styles and Coxon (2006). As is true for laboratory analyses in general, this illustrates the need for caution when comparing soil analyses from widely differing regions, even if the tool kit provides good relative comparisons of sites within a region and is predictive of maize yields.

### 2.4.2 Ability of the soil tool kit measured properties in explaining maize grain yield

In addition to validating our tool kit against corresponding lab methods, we evaluated the ability of the tool kit measures to predict crop productivity. Our model selection approach sought to explore which of the soil factors evaluated here most influence grain yield, and then compare the tool kit outputs to standard laboratory results within these statistical models. By comparing the same soil properties measured in different settings, we showed that the tool kit can explain variability in grain yields just as well as standard methods, suggesting that the properties assessed are valuable for explaining relevant soil processes associated with crop growth and overall productivity across a range of smallholder farm contexts. POXC and available P were the most significant factors in multiple regression models explaining variability in yields, as well predicting maize yield in direct Pearson correlations. This aligns well with other studies showing that POXC can predict maize yield and is sensitive to changes in management strategies that promote SOC accumulation in the soils (e.g., Culman et al., 2013; Hurisso et al., 2016). The ability of available P to predict grain yields is not entirely surprising, since P is often the most limiting nutrient to crop productivity in highly weathered soils like those considered in Kenya (Margenot et al., 2016). As such, if organizations or farmer researchers can measure these properties easily, then they are better positioned for understanding and managing spatial heterogeneity in their soils.

### 2.4.3 Understanding management impacts on soil function

When comparing the effects of a high residue biomass legume (*L. purpureus*) to one with relatively low residue inputs (*P. vulgaris*) in the rotation, we observed significant differences only in the quantity of POM recovered from the soil. The observed impact on POM is likely due to the high amount of biomass that *L. purpureus* leaves behind after harvest (approximately a ten-fold difference) as well as increased residues left by maize that tended to grow better following positive effects of *L. purpureus* on maize biomass (data not shown). Due to the speed of SOM mineralization in these tilled tropical soils, increases in POM that are meaningful from the standpoint of soil health could have occurred in our study plots due to these increased residue inputs, while not yet causing a detectable change in POXC that would indicate building of more stable carbon stocks in soils. In a long-term experiment carried out by Gregorich et al. (2001) where legumes were added in rotation with maize, there was 40% greater C observed below the plow layer (20-70 cm depth) compared to maize monoculture. This supports the contribution of legume residues and residual effects to POM, as such legumes with higher biomass such as *L. purpureus* would contribute more to POM. As residue returns from legumes and other sources are increasingly prioritized to contribute to SOM pools for soil health, others have suggested that POM is a potentially important indicator of soil quality, as it is sensitive to management practices such as tillage, rotation and residue inputs (Kantola et al., 2017; Hatfield et al., 2018; Lavallee et al., 2020). We note that the POM measurement tested here is a relatively simple procedure and could be a good option for farmer-managed soil health evaluation with a positive aspect of easy visualization by farmers of a carbon pool that is amenable to management. The POM test using simple materials and procedures is also promising for generating data over wide areas with high levels of soil and management heterogeneity.

Despite impacts on POM, the legume treatment did not impact other physical and chemical properties within the timeframe considered here. This result was not entirely surprising given the relatively subtle differences between treatments and the relatively short timeframe considered here. For example, Drinkwater (1998) found that while yield benefits of legume cereal rotations can be realized within a short period, significant changes to the SOC pool and other soil chemical properties occur when residue additions or other practices favorable to organic matter accrual are repeated over longer time periods (e.g., 6 to 15 years). Even though no significant differences were noted for soil health indicators, indicators in lablab-amended plots were uniformly higher than those with preceding *P. vulgaris*, which suggests that soil properties could be starting to change and with enough time and continued incorporation *of L. purpureus* biomass, clearer differences between treatment may emerge.

### 2.4.4 Implications for future research and management

As noted by Barrios et al. (2006), data gathering tools, such those tested here, can empower farmers and small research organizations to manage and subsequently monitor soil health for informed decision making. Our soil tool kit can be used to track the impacts of promising practices and/or provide early warning signs of soil fertility decline in smallholder systems. However, as noted from the relatively small (thus not significant) treatment differences for many parameters, it might be good to measure impacts after a longer period following legume integration or considering more divergent management practices. Evaluation of baseline soil characteristics before implementation of short-term research trials is another potential use for our tool kit. Such trials are increasingly being set up by farmer research networks across the region and information generated by the tool kit could help inform which practices work better under which contexts, and thus improving the effectiveness of soil restoration strategies in a variety of smallholder farming settings. This fits with Coe et al. (2016) who suggested that a range of agronomic management options should be developed and offered to suit a variety of contexts, so as to reduce risks for smallholders adopting new practices. Our soil tool kit offers one approach to better understand soil heterogeneity within and between farms and help identify options that better optimize soil management for each context.

Beyond supporting local research needs and management decisions, our soil tool kit provides an entry point for education and engagement with stakeholders on soil health discussions in the smallholder sector. Measurements such as pH, POM and aggregate stability can be easily adapted for a workshop setting to provide stakeholders with better visual appreciation of differences between management practices. The tool kit can help facilitate dialogue and education and enables farmers to better contribute in efforts to improve their soil health. Thus far, our soil tool kit has been successfully used in workshops in both western and eastern Kenya, Peru, Tanzania, Malawi, and elsewhere for baseline assessment of soils before setting up of field trials. Such participatory engagement of all stakeholders allows for co-learning and sustainable management of soil health (Kristjanson et al., 2017).

The analyses tested here provide a rapid and more affordable way of measuring soil properties and using readily available equipment. While equipment and reagents are simple and low-cost, some methods in the tool kit require training to understand the concepts behind each test and ensure repeatability, while others, such as the POM and aggregation, can more easily be done by farmers with more basic training and simpler materials to track progress. For some of the tests such as POXC and available P, there is also an advantage to doing samples in batches at the same time to increase comparability and reduce variation from analysis to analysis. As such, we suggest that our tool kit is most appropriate for the interface between extension/field officers and individual farmer-researchers who can coordinate to decide on which tests are best done within different settings. This can be used as a basis for assessing impacts of management on soil quality and long-term implications for sustainable crop production in these vulnerable systems.

More specifically, the tool kit provides reliable data at lower cost and more conveniently. This allows farmers and those they work with to better understand soil contexts and constraints in heterogeneous farm environments such as those often managed by smallholders. Historically, most of the farmers and the people they work with have relied on blanket recommendations that may lead to insufficient nutrients added or over working of soils. Assessing changes in soil health status following technology implementation assists in decision-making to improve practices and scale them out.

## 2.5. Conclusions

Our findings suggest that a tool kit with simplified soil analyses provided a robust, quantitative assessment of multiple soil parameters across a wide range of smallholder contexts. Most notably, pH and POXC were highly correlated with comparable tests run at regional laboratories. An adapted Olsen test for available P compared well to soil tests normally done in east Africa and the Andes, despite an adapted field method and the use of a different extractant in the case of Kenya. The tool kit P test also explained maize yield in Kenya at least as well as the standard test. Tool kit POXC was correlated with total organic C in soil from both Peru and Kenya, which suggests promise for POXC to provide a proxy measurement to detect changes in SOM. Our test for POM, an important and dynamic SOM pool, was more sensitive in measuring management differences in these farms than any of the standard tests run at a reputable regional soil laboratory in Kenya. This suggests that our tool kit may offer important additional insight to detect early changes in SOM and overall soil health; however, further study is required. The tool kit measurements were significantly correlated to maize yield across all farms and could explain variability in maize grain yield as well as or better than standard laboratory methods, thus further confirming the utility of this tool for assessing overall soil health across treatments and farms and guiding management to address constraints such as available P or SOC. Our tool kit offers great potential to empower to NGOs, farmer organizations, rural universities and research institutions to better evaluate the impact of new agricultural options being tested and to understand soil contexts in which they work, thus avoiding blanket recommendations and contributing to a positive and knowledge-intensive changes in farmer practices that support soil health.

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# Chapter 3: Examining the contributions of maize shoots, roots, and manure to stable soil organic carbon pools in tropical smallholder farming soils

## 3.1 Introduction

Smallholder farming systems often experience low availability of organic matter and nutrient inputs, with long-term implications for soil health (Tittonell et al., 2005). At the same time farmers must manage trade-offs between soil fertility management and other farm enterprise considerations such as feeding livestock (Ojiem et al., 2005; Rusinamhodzi et al., 2015), which has contributed to low and declining soil organic carbon (SOC) stocks. 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 (Kafesu et al., 2018). 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 (Kamau et al., 2019; Mungai et al., 2016). By enhancing organic matter inputs and/or slowing the loss of SOC via decomposition, these methods have the potential to significantly improve C stocks in smallholder soils (Nyawade et al., 2019; 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 versus feeding to animals and then applying manure to the field results in better stabilization of SOC over time (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 pools, 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 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 more likely to 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 management recommendations for supporting soil health and 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 quality of organic inputs influenced stabilization of C in the slow and passive C 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, Kirby et al. (2013; 2014) found that additions of 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 (Nyamasoka-Magonziwa et al., 2020), it is the passive pools that reflect more stable SOC and long-term SOC 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. 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 is 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 SOC 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 sustain SOC and achieve 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 by using a $^{13}C$ a natural abundance approach. Specifically, we used an incubation experiment to: i) assess the incorporation of maize shoots versus maize-derived cattle manure into distinct soil SOC pools (mentioned above); ii) compare the potential contribution of maize root-derived C relative to maize shoots to key soil C pools; and iii) 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 tropical soils. We hypothesized that manure derived-C is stabilized more readily compared to maize shoots. We also hypothesized that root-derived C results in more C stabilization than maize shoots or manure. Finally, we anticipated 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.

## 3.2 Materials and Methods

### 3.2.1 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 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 considered ferralsols and 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 %, δ $^{13}$C signature of -24, and a pH of 4.6 (measured in a 2:1 deionised water:soil suspension).

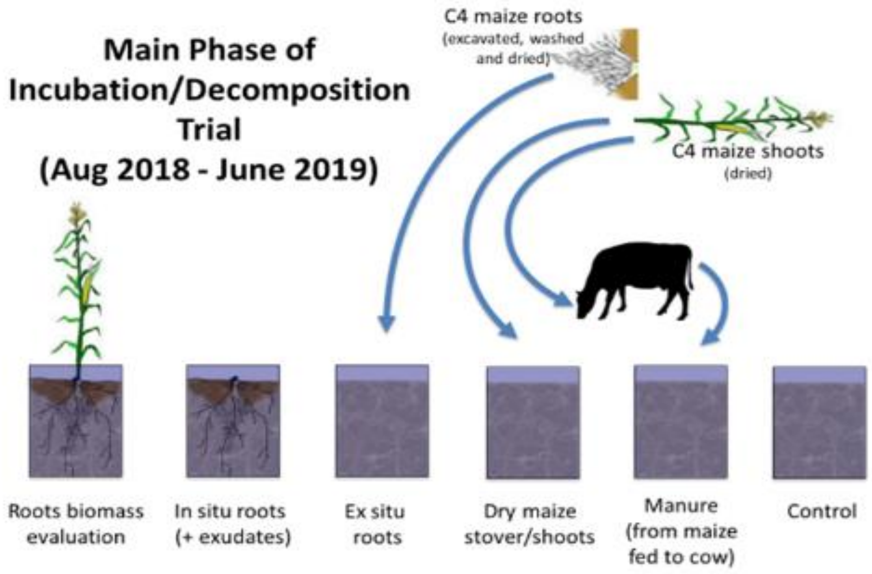

**Figure 3.1**: Study configuration for a $^{13}$C incubation experiment in an oxisol in western Kenya with the following treatments: 1) maize shoots 2) ex-situ maize roots (collected from a nearby field), 3) in-situ maize roots (grown within the same soil), 4) manure (from cattle fed with maize), and 5) a control with no residue additions. Each of the residue treatments were applied with or without mineral fertilizer additions

### 3.2.2 Experimental design and set-up

The experiment was comprised of five 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) ex-situ maize roots (collected from a nearby field), 3) in-situ maize roots (grown within the same soil), 4) manure (from cattle fed with maize shoots), and 5) a control with no residue additions (Fig. 3.1). 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 3.1 and additional detail below). The fertilized control (i.e., no residue) treatment received N, P, and S additions equivalent to the maize shoot treatment, which required the greatest addition of mineral N, P, and S additions to achieve the desired stoichiometry. This resulted in full factorial design with ten treatments (five residue treatments x two fertilizer/stoichiometry levels) each with five replicates and arranged in a completely randomized design.

Seventy 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 to help provide drainage) and the mixture packed down gently to achieve a bulk density of approximately 1.2 g cm$^{-3}$. In thirty of the seventy pots, four maize seeds were planted per pot, and then all seventy pots were watered with equal amounts of water and allowed to drain. After 2 weeks of establishment the seedlings were thinned to one plant per plot and allowed to grow for 5 additional weeks. The other forty pots were maintained without any plants during the preincubation stage. All pots were maintained at similar moisture and temperature levels by weighing a representative sub-sample of pots (with and without plants) on a weekly basis and adding the average amount of water required to achieve 80 % of field capacity in each group of pots.

After 7 weeks of maize growth, ten pots from the thirty pots planted with maize were randomly selected for the in-situ root treatment. Maize shoots from the ten pots were removed by cutting the plants close to the soil surface with shears. The aboveground biomass was removed and the soils with in-situ roots were gently mixed with a trowel to simulate tillage. Roots in the remaining 20 pots were destructively sampled to determine the average amount of root biomass produced by the maize plants after 7 weeks of growth. This was accomplished by removing all visible roots from the soil, while smaller roots were captured by submerging the soil in water and sieving through a 0.25 mm sieve. The roots were patted dry with a paper towel, the fresh weight recorded, and then roots were oven dried at 60 $^{o}$C for dry biomass determination. In-situ root biomass additions for this treatment were estimated to be approximately 6.6 g per pot (oven dried biomass) or a rate of approximately 2.6 Mg ha$^{-1}$.

For treatments with maize shoots and ex-situ 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 (as described above) 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 clean C4 signature, two cows under zero-grazing were fed with pure maize stover for 3 days. The manure produced in the first two 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).

Organic inputs (shoots, manure, ex-situ 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 that had not had plants growing in them for the previous 7 weeks. 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.

**Table 3.1**: 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** | | | | **$\delta\,^{13}C$** | **Nutrient additions** | | |
|---|---|---|---|---|---|---|---|---|
| **Organic input** | **C** | **N** | **P** | **S** | | **N** | **P** | **S** |
| | ------------- % ------------ | | | | | ----- g $pot^{-1}$ ------ | | |
| Shoots | 52.7 | 0.79 | 0.75 | 0.09 | -13.33 | 0.88 | 0.24 | 0.16 |
| 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 | 0.98 | 0.27 | 0.18 |
| In-situ roots* | 53.3 | 0.62 | 0.10 | 0.12 | -12.83 | 0.21 | 0.06 | 0.04 |
| Control | N/A | N/A | N/A | N/A | N/A | 0.88 | 0.24 | 0.16 |

* N, P and S concentrations for in-situ roots were assumed to be the same as ex-situ roots, but we acknowledge that rhizodeposition could lower the C:N:P:S ratio.

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 that shaded surface soil in the region would typically be exposed to.

### 3.2.3 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, cooled and then sieved to 2 mm. This follows methods by outlined by Haddix et al., (2020), who found the heating treatment to not significantly affect C content of the different fractions.

### 3.2.4 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 according to Soong and Cotrufo (2015) - Fig. 3.2. 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 ºC. 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 °C.

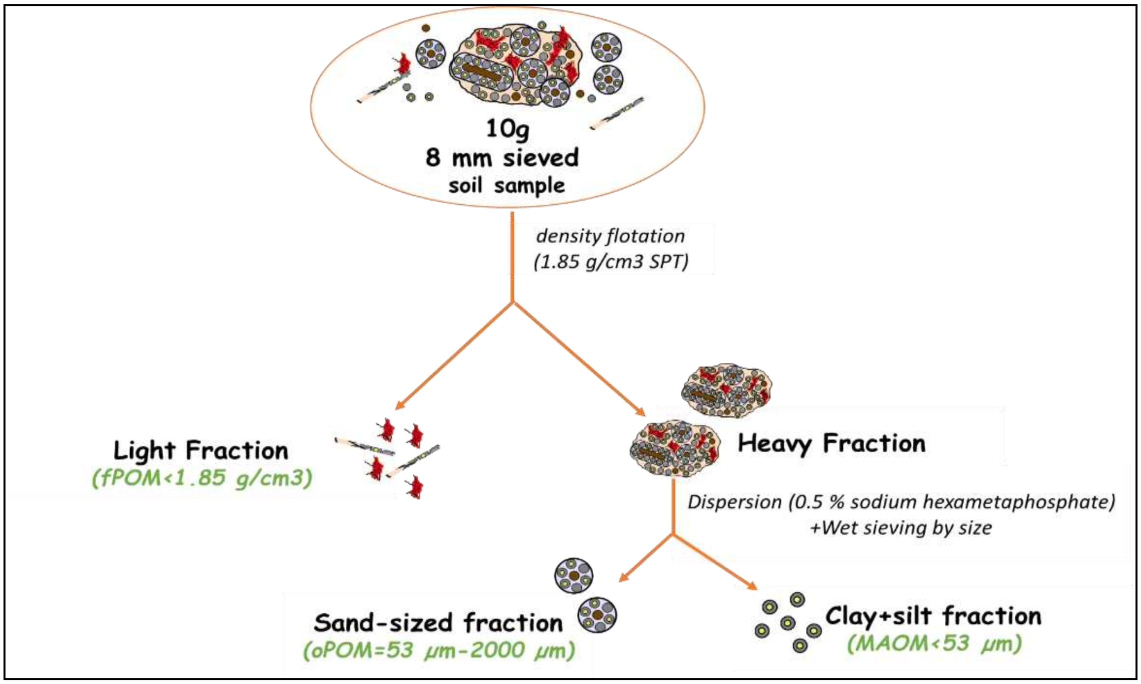

**Figure 3.2**: Fractionation of soil by density and size following a 48-week long incubation of different types of organic input in western Kenya. fPOM is free particulate organic matter, oPOM is occluded particulate organic matter, and MAOM is mineral associated organic matter and SPT is sodium polytungstate. Adapted from Fang et al., 2019.

### 3.2.5 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 to each residue treatment (due to differences in C concentration for the different residues or the relatively small amount of biomass added in the in-situ root treatment), the proportion of added 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 quantity added C that was stabilized (g C $kg^{-1}$ soil $g^{-1}$ C input), *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 $kg^{-1}$ soil basis. This new C was calculated both on per soil fraction basis, 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.

### 3.2.6 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 verified, and ln transformations applied as needed. Tukey's honestly significance difference at ($p<0.05$) was used for mean separation using post hoc tests from the lsmeans package (Lenth 2016). All analyses were conducted using the R statistical package v3.2.2 (R Core Team, 2019).

## 3.3 Results

### 3.3.1 Treatment effects on total C and C:N ratio

Of the three fractions, fPOM was generally the most enriched in total C (range: 202-235 g C kg $^{-1}$ soil fraction), followed by MAOM (range: 43.5-45.3 g C kg $^{-1}$ soil fraction) and then oPOM (range: 4.8-5.9 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 3.2). 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 ($p=0.003$; Table 3.2) and MAOM ($p=0.04$) with a tendency for manure and ex-situ roots to be reduced more than shoots by nutrient additions (nutrient x residue interaction, $p=0.06$). 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 (19.2-24.1).

### 3.3.2 Recovery of maize-derived C in soil fractions

Residue type had significant effects on $\delta^{13}C$ values in all the fractions, such that the in-situ treatments (with and without fertilizer) had less maize-derived residue (indicated by more negative values) than other treatments across all fractions and bulk soil (Table 3.3). Nutrient additions only had significant effects in the MAOM fraction, such that adding nutrients led to slightly less maize-dervived C (more negative $\delta^{13}C$ values) than without nutrient additions. There was a significant residue type by nutrient interaction for the oPOM fraction, such that the addition of nutrients resulted in less maize-derived C for ex-situ roots, in-situ roots, 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 treatmetns, the proportion of C from the added inputs (i.e., f value; Table 3.3) was significantly affected by residue type in all fractions, where in-situ root treatments had lower f values compared to the other treatments; for example, less than 10% of fPOM was maize-derived in the in-situ root treatment, while ~ 25 % of the fPOM was maize-derived (on average) for the other residue treatments, with higher rates of addition. Contrary to our hypothesis, nutrient additions resulted in significantly lower f values across treatments for the MAOM fraction. There was also a significant residue by nutrient interaction for oPOM ($p = 0.02$), 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.

As reported above, the relatively low biomass input associated with the in-situ root treatment led to a weak $^{13}C$ signal of maize-derived C in the various SOC pools (Table 3.3). Due to this low signal and relatively high variability associated with this treatment, we excluded this treatment from subsequent analyses that examined treatment effects on C within the different SOC fractions and bulk soil (reported below).

When looking at new C derived from residue additions in the different C pools on a per fraction basis, fPOM was highly variable within and across treatments ranging from 7.2 to 19.1 g

C kg$^{-1}$, with no significant treatment effects (Table 3.3). 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=0.02), 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=0.01) and nutrient additions (p=0.008; Fig. 3.3). Averaged across nutrient additions, shoot-derived C was stabilized at twice the rate of manure-derived C and 1.6 times more than ex-situ root C (Fig. 3.2a), 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. 3.2b).

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=0.03) with shoots having the highest amount of new C stabilized (2.7 and 1.7 times more new C than for manure and ex-situ roots; respectively), while addition of nutrients reduced C stabilization by 30% on a whole soil basis relative to soils with no fertilizer addition (Table 3.3). We note most new C in manure and ex-situ root treatments was found in fPOM, while most new C from shoots was found in the MAOM fraction.

Table 3.2: 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 (in-situ and ex situ) 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 | 11.6 |
| | | (15.4) | (0.255) | (1.680) | (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) | (0.274) | (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) | (2.92) | (0.307) | (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) | (0.200) | (1.71) | (0.49) | (0.41) | (1.71) | (1.86) | (0.099) | (0.03) | (0.25) |
| Ex-situ roots | No | 227 | 5.54 | 44.5 | 28.8 | 1.70 | 2.75 | 22.3 | 24.1 | 12.6 | 12.1 | 11.8 |
| | | (3.81) | (0.311) | (0.350) | (1.26) | (0.20) | (0.31) | (1.63) | (1.55) | (0.81) | (0.04) | (0.09) |
| Ex-situ 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) | (0.365) | (0.79) | (0.27) | (0.16) | (1.39) | (1.57) | (0.331) | (0.13) | (0.22) |
| In-situ roots | No | 235 | 5.38 | 45.1 | 26.9 | 1.39 | 2.97 | 19.8 | 22.4 | 12.8 | 12.1 | 11.7 |
| | | (15.5) | (0.463) | (0.743) | (1.16) | (0.25) | (0.25) | (0.29) | (3.26) | (0.08) | (0.05) | (0.06) |
| In-situ roots | Yes | 202 | 4.82 | 43.9 | 29.8 | 1.10 | 2.48 | 21.0 | 19.2 | 12.9 | 12.3 | 11.5 |
| | | (30.4) | (0.274) | (0.190) | (1.17) | (0.18) | (0.16) | (1.25) | (1.96) | (0.07) | (0.03) | (0.17) |
| *p-values* | *Residue* | *ns* | *ns* | *ns* | *ns* | *ns* | *ns* | *ns* | *ns* | *ns* | *ns* | *ns* |
| | *Fertilizer* | *ns* | *ns* | *ns* | *ns* | *ns* | *ns* | *ns* | *ns* | *ns* | *0.04* | *0.003* |
| | *Residue x Fertilizer* | *ns* | *ns* | *ns* | *ns* | *ns* | *ns* | *ns* | *ns* | *ns* | *ns* | *0.05* |

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 3.3**: 13C, f value and New Carbon derived from residue additions in soil fractions and the whole soil following an 11-month incubation experiment a using $^{13}$C natural abundance approach, with a C4 maize-based residues (shoots, manure, ex-situ roots, in-situ 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 fraction basis** | | | **New Carbon whole soil** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **fPOM** | **oPOM** | **MAOM** | **Bulk Soil** | **fPOM** | **oPOM** | **MAOM** | **Bulk Soil** | **fPOM** | **oPOM** | **MAOM** | **fPOM** | **oPOM** | **MAOM** |
| | | ------------------------‰----------------- | | | | | | | | *-----g C kg $^{-1}$ soil fraction----* | | | *-------g C kg $^{-1}$ whole soil g $^{-1}$ C added in 1 kg soil ---------* | | |
| Shoots | No | -23.7 | -24.1 | -23.7 | -23.4 | 0.136 | 0.050 | 0.0180 | 0.029 | 17.22 | 0.076 | 0.198 | 0.16 | 0.15 | 0.39 |
| | | (0.58) | (0.07) | (0.02) | (0.06) | (0.05) | (0.01) | (0.002) | (0.006) | (2.40) | (0.008) | (0.027) | (0.05) | (0.02) | (0.04) |
| Shoots | Yes | -20.9 | -23.8 | -23.7 | -23.3 | 0.364 | 0.098 | 0.0140 | 0.045 | 17.30 | 0.131 | 0.157 | 0.43 | 0.25 | 0.33 |
| | | (1.30) | (0.06) | (0.03) | (0.13) | (0.11) | (0.01) | (0.003) | (0.01) | (4.60) | (0.013) | (0.036) | (0.10) | (0.03) | (0.09) |
| Manure | No | -22.1 | -24.0 | -23.7 | -23.7 | 0.267 | 0.080 | 0.0100 | 0.008 | 16.60 | 0.120 | 0.135 | 0.53 | 0.22 | 0.19 |
| | | (0.83) | (0.08) | (0.01) | (0.05) | (0.07) | (0.01) | (0.001) | (0.003) | (4.27) | (0.013) | (0.014) | (0.18) | (0.03) | (0.02) |
| Manure | Yes | -22.9 | -24.0 | -23.8 | -23.3 | 0.198 | 0.070 | 0.0030 | 0.045 | 13.30 | 0.126 | 0.042 | 0.36 | 0.21 | 0.07 |
| | | (0.47) | (0.06) | (0.03) | (0.17) | (0.04) | (0.01) | (0.001) | (0.020) | (1.84) | (0.016) | (0.199) | (0.09) | (0.03) | (0.04) |
| Ex-situ | No | -20.9 | -23.8 | -23.7 | -22.9 | 0.339 | 0.091 | 0.0120 | 0.073 | 19.10 | 0.127 | 0.135 | 0.59 | 0.26 | 0.26 |
| | | (0.53) | (0.16) | (0.05) | (0.19) | (0.04) | (0.13) | (0.003) | (0.020) | (2.22) | (0.025) | (0.036) | (0.12) | (0.06) | (0.07) |
| Ex-situ | Yes | -21.1 | -24.0 | -23.8 | -23.2 | 0.320 | 0.075 | 0.0070 | 0.05 | 18.10 | 0.094 | 0.082 | 0.64 | 0.19 | 0.17 |
| | | (1.00) | (0.21) | (0.03) | (0.19) | (0.08) | (0.02) | (0.002) | (0.020) | (5.31) | (0.021) | (0.022) | (0.21) | (0.05) | (0.04) |
| In-situ | No | -24.2 | -24.8 | -23.8 | -23.8 | 0.096 | 0.015 | 0.0030 | 0.009 | | | | | | |
| | | (0.89) | (0.09) | (0.03) | (0.09) | (0.07) | (0.01) | (0.001) | (0.004) | | | | | | |
| In-situ | Yes | -24.4 | -24.7 | -23.9 | -23.7 | 0.078 | 0.015 | 0.0001 | 0.01 | | | | | | |
| | | (0.87) | (0.09) | (0.01) | (0.07) | (0.05) | (0.01) | (0.000) | (0.004) | | | | | | |
| *p-values* | *Residue* | *0.006* | *<0.001* | *<0.001* | *<0.001* | *0.01* | *<0.001* | *<0.001* | *<0.001* | *ns* | *ns* | *0.01* | *ns* | *ns* | *0.003* |
| | *Fertilizer* | *ns* | *ns* | *0.012* | *ns* | *ns* | *ns* | *0.003* | *ns* | *ns* | *ns* | *0.008* | *ns* | *ns* | *0.08* |
| | *Residue x Fertilizer* | *ns* | *0.03* | *ns* | *0.09* | *ns* | *0.02* | *ns* | *0.08* | *ns* | *0.02* | *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.

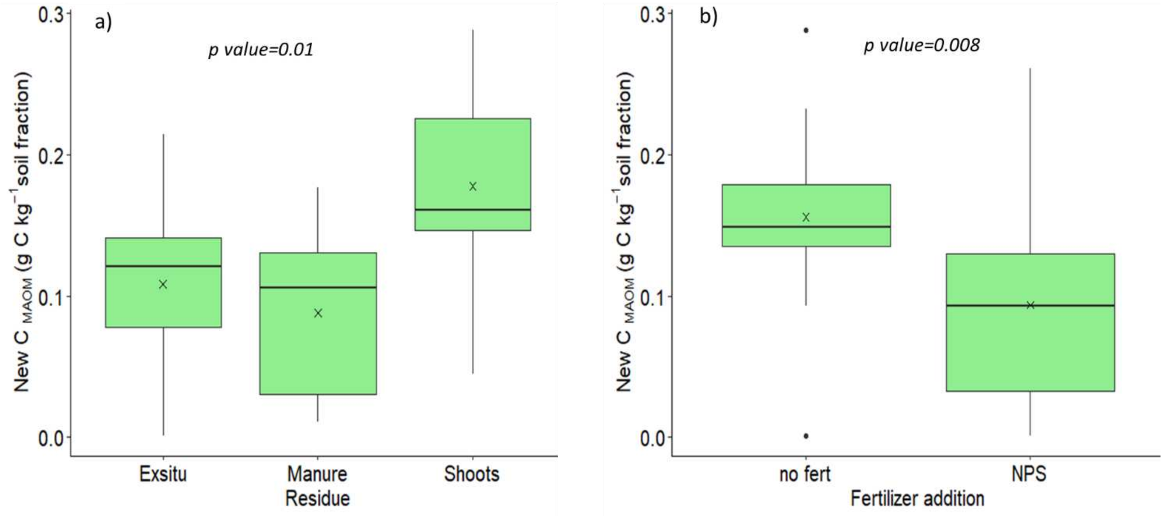

**Figure 3. 3**: New carbon stabilized from organic input treatments in the mineral-associated organic matter (MAOM) soil fraction following an 11-month incubation experiment a using $^{13}$C natural abundance approach, with a C4 maize-based residues incorporated into a C3, forest-derived, soil in western Kenya: a) effect of residue type (averaged across fertilizer additions of N, P, and S) and b) effect of N, P and S additions (averaged across residue types). Boxes are the 25th and 75th percentiles. X indicates treatment means, while the lines dividing the boxes are the median values for each treatment and dots are outliers.

## 3.4 Discussion

Our study sought to understand how varying forms 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 would enhance C stabilization of distinct organic inputs.

### 3.4.1 Residue quality as a driver of SOC dynamics

Separating the soils into size and density fractions offers important insight for understanding SOC dynamics, as these fractions have distinct characteristics and contributions to SOC (Cotrufo et al., 2019). Our findings indicate that while different types of organic residues resulted in minimal impacts on fPOM and oPOM fractions, maize shoot-derived C was more prevalent in the MAOM fraction than C derived from maize roots or manure. This is relevant, since MAOM has the slowest turnover of 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 gives an indication of 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 preferentially stabilized compared to lower quality residues (e.g. ex-situ 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 had no effects on the stabilization of C in different fractions (Gentile et al., 2011). These apparently conflicting findings indicate that diverse mechanisms are at play and that organic matter processing in soils is likely controlled by a variety of factors.

Residue quality involves more than just the C:N ratio and refers 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 versus shoots versus ex-situ roots. Therefore, there are likely other (e.g., structural) characteristics that influence organic matter turnover and stabilization by soil microbes. In their incubation of sorghum shoot versus ex-situ root residues, Fulton-Smith and Cotrufo (2019) found that shoots resulted in greater new C in MAOM than roots, similar to our study. 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. Both the lignocellulose index and lignin content have been shown to be the good predictors of organic matter decomposition rates (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. 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 our findings.

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 may be related to the fact that our findings rely more on ex-situ roots that did not grow in place. Other mechanisms of stabilization that are unique to roots growing in place, such as being in close proximity to soil particles, increased aggregation and rhizodeposition, were not realized in our ex-situ root treatments. Unfortunately, our in-situ root treatment was not so insightful because of the relatively low and variable inputs, resulting in a weak $^{13}C$ signal, we suspect that we might have seen preferential stabilization of in-situ root C relative to other inputs given more time and/or a stronger $^{13}C$ label, for example, by using an isotope enrichment approach with labelled $^{13}CO_2$ (e.g., Balesdent and Balabane, 1996).

### 3.4.2 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. Our results therefore 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) 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 due 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 say at the mid-point of the experiment we might have seen greater stabilization with N, P, and S additions, as reported by Kirby et al. (2013) in their incubation experiment that lasted just 84 days.

### 3.4.3 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 represents a choice that farmers make with 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). Beyond this initial C loss, 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 on maintaining crop residues on the soil surface, especially as mulch (e.g., via erosion control, reduced evaporative losses), then this implies clear tradeoffs for soil health. Considering, however, that livestock are important (for 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 so 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, 2017). Despite our findings indicating lower stabilization of manure derived-C, manure can still play important role in managing soil health apart from maintaining SOC, such as supporting crop nutrition and soil aggregation better than crop residues (Dunjana et al., 2012; Miller et al., 2012; Yagüe et al., 2016). Manures 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 perhaps 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.

### 3.5 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 inconclusive and urge further research using $^{13}C$ enrichment studies to provide more definitive information about the long-term fate of different residue types in soils, especially root-derived C. Nutrient additions to balance the stoichiometry of residues do not appear to support SOC in the long-term and may actually decrease the incorporation of C within the stable MAOM fraction, at least in the timeframe and soil conditions considered here. There is still need for further research to quantify the dynamics of SOC from different organic sources available in smallholder farming communities so as to better utilize those most beneficial to soil health.

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# Chapter 4: Organic nutrient source allocation and use in smallholder farming communities: what are we missing?

## 4.1 Introduction

On many smallholder farms around the world, crop yields remain low (i.e., around 1 Mg $ha^{-1}$ for staple cereals; Tittonell and Giller, 2013) or are declining due to inherently poor soils and inadequate soil fertility management, among other factors (Sheahan and Barrett, 2017; Khalid et al., 2019). Poor soil health thus threatens the achievement of Sustainable Development Goal Two (SDG2), which aims to end hunger, achieve food and nutritional security, and promote sustainable agriculture. Recycling organic nutrient sources (ONS) produced on farm by applying them to soils, with or without mineral fertilizer additions, can increase soil organic matter (SOM) and nutrient cycling, and hence improve soil health (Agegnehu and Amede, 2017). The role of organic amendments in sustainable agriculture is highly relevant and understanding how they are managed and implications for soil fertility in different farming systems and contexts can contribute to meeting these SGD2 targets.

Smallholder farmers produce and manage organic resources such as crop residues (Valbuena et al. 2012; Turmel et al. 2015), animal manure (Rufino et al., 2007) and farmyard manure/compost on farm. They may also collect off-farm organic resources, such as forest litter or plant residues

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from field margins, to apply in their soils as a key source of nutrients for their crops (Nekesa et al., 2007; Nganga et al., 2020). Different types of organic inputs play distinct roles in the improvement of soil health by increasing SOM and in providing nutrients to support crop productivity (Rusinamhodzi et al., 2016;Wood et al., 2018, Vanlauwe et al., 2019). Studies in western Kenya have demonstrated the potential that ONS have to improve nutrient use efficiencies and ultimately crop yields, especially when combined with mineral fertilizers (Vanlauwe et al., 2011; Mutuku et al., 2020). Studies by Lu et al. (2020) and Murphy et al. (2016) demonstrate that residue retention led to increased crop yields, soil organic matter content and nutrient use efficiency e.g., the latter found that residue retention led to roughly twice as much fertilizer nitrogen making it into maize plants and a 40% increase in overall 'system' recovery (plant + soil). A range of ONS have long been used by farmers in their cropping fields and home gardens, sometimes in combination with mineral fertilizers (Palm et al., 1997). More recently, soil management approaches such as conservation agriculture and integrated soil fertility management further promote the use of ONS to manage soil fertility and overall health. Practices involving ONS have been shown to minimize losses through leaching and erosion and improve nutrient use efficiency (Agegnehu and Amede, 2017).

Farmers are often faced with decisions on how to allocate ONS around the farm. Some may retain all the residues produced in the plot where they grew, applying them directly to the soil, whilst others may transfer them to other plots (Rusinamhodzi et al., 2016). Farmers with livestock may choose to feed some or all of the residues to livestock and then apply the manure produced directly (or composted) as an ONS (Rufino et al., 2007). Some ONS can also be used as fuel and building materials, thus highlighting numerous potential tradeoffs for ONS allocation, with important implications for nutrient management and soil health. For example, if maize residues are exported from a plot season after season, without other inputs coming in, severe nutrient and SOM depletion will occur resulting in poor crop yields. Several studies have assessed the general management of crop residues and manure at the farm level in East Africa and particularly in western Kenya (e.g. Tittonell et al., 2005; Valbuena et al., 2012; Rodriguez et al., 2017). These studies have focused largely on the issue of organic input allocation and associated tradeoffs and pose the question of which is the best way to allocate organic resources to benefit soil health, livestock production and/or off farm trade.

Meanwhile, other studies have focused on practices in the use of ONS and have considered determinants of adoption of ONS, largely focusing on the resource status of farmers (Pedzisa et al., 2015, Adolwa et al., 2019). Economic resource endowment of farmer households has been shown to be a key driver of nutrient management practices, specifically the use of ONS in smallholder farms because it influences the quantity of organic resources available (Mugwe et al., 2009, Liu et al., 2018). For example, the more livestock a farmer has, the more manure they can put in their field, but the less crop residues they may retain in-field due to need for feed (Duncan et al., 2016). More resource endowed farmers might also allocate less ONS to the field since they can afford to purchase mineral fertilizers. However, beyond farm resource endowment, there are other socio-economic factors such as land tenure, access to local extension and training. A clearer understanding of socio-cultural variables such as adherence to social norms and social networks that influence ONS allocation is needed (Mponela et al., 2016; Leonhardt et al., 2019). These additional factors remain poorly understood and thus may be obscuring constraints and opportunities for more effective and accessible ecological nutrient management within smallholder farming systems. A clearer understanding is required of socio-cultural variables that could influence decisions on how organic resources are allocated around the farm. Such understanding can help to foster socio-ecological based approaches that are required to understand the adaptive capacity (i.e., ability to cope with environmental and societal changes) of agricultural systems (Folke et al., 2002). This adaptive capacity is especially important for soil nutrient management to achieve zero hunger by the most vulnerable farming communities in smallholder farming systems.

In addition to socio-cultural factors at a household scale, it is important to recognize that environmental factors (agroecological zone and within-farm soil variability influenced by preferential allocation of ONS to some plots) affect ONS management in smallholder systems. Communities vary in terms of land holding, farming systems, organization and social norms when comparing different agroecological regions (Tittonell et al., 2005). Meanwhile, at the farm scale, soil fertility gradients are created due to preferential allocation of ONS in different plots, and this creates feedbacks that cause fertile soils to improve and infertile soils to become more depleted creating within-farm variability (Zingore et al., 2007, Vanlauwe et al., 2007; Masvaya et al., 2010). The perception of plot fertility resulting from the gradients and distance from homestead which influences labor available also determine where farmers allocate their ONS (Caulfield et al., 2020)

Given the interplay of social and environmental factors at different scales, smallholder farmers occupy very specific niches embodying socio-economic and socio-cultural factors as well as agroecological contexts and variability that they themselves may create on their farms (Ojiem, 2005). As such, it is helpful to group farmers/farms that are similar (via typologies or other means) to better understand their utilization of soil fertility practices and/or to generally characterize farmers (Alvarez et al 2018). While resource endowment is clearly important in developing such farmer typologies (Tittonell et al., 2005, Chikowo., et al 2014), socio-cultural variables may also influence ONS management (Kolawole, 2013, Tittonell et al., 2005) and it is important to understand how and to what extent such variables also influence the formation and characterization of ONS management. It is also important to link environmental and socio-economic approaches for different contexts in addressing issues of food security and soil quality (e.g. Webb et al., 2013; Kristjanson et al., 2017; Balch et al., 2020). Research in this area can benefit greatly from employing both quantitative and qualitative approaches to understanding the complex patterns of socio-economic status and agricultural development.

This study sought to improve our understanding of how the socio-economic, socio-cultural and environmental contexts influence decisions on ONS management in representative smallholder farms of western Kenya, so as to inform strategies for achieving sustainable soil nutrient management for "zero hunger" in vulnerable communities. Specifically, we wanted to understand: i) how ONS are allocated and cycled at farm and community levels in contrasting agroecological regions, and ii) the dominant socio-economic and socio-cultural factors affecting ONS allocation and cycling for different farm types, within a farm typology based on resource endowment, adherence to social norms, and connectedness to networks regarding soil management. We hypothesize that resource endowment together with key socio-cultural variables (e.g. gender, network connections, adherence to social norms, extension, training) and biophysical aspects, such as differences in agroecological contexts (location - which influences climate, soils, and farming systems and perceived soil fertility), are also significant determinants of ONS management. In summary, we hypothesize that these different determinants are expressed as farm types that help to explain different ONS management strategies in the mixed crop-livestock systems of western Kenya.

To address these questions, we conducted focus group discussions followed by quantitative farmer interviews in a mixed methods research approach carried out in three communities within contrasting agroecological zones in western Kenya.

## 4.2 Methodological Approach

### 4.2.1 Study Sites

The study was carried out in western Kenya in the counties of Nandi, Busia and Vihiga (Figure 4.1). Located in different agroecological zones, the three counties experience distinct climates (Table 4.1) and have unique farming systems.

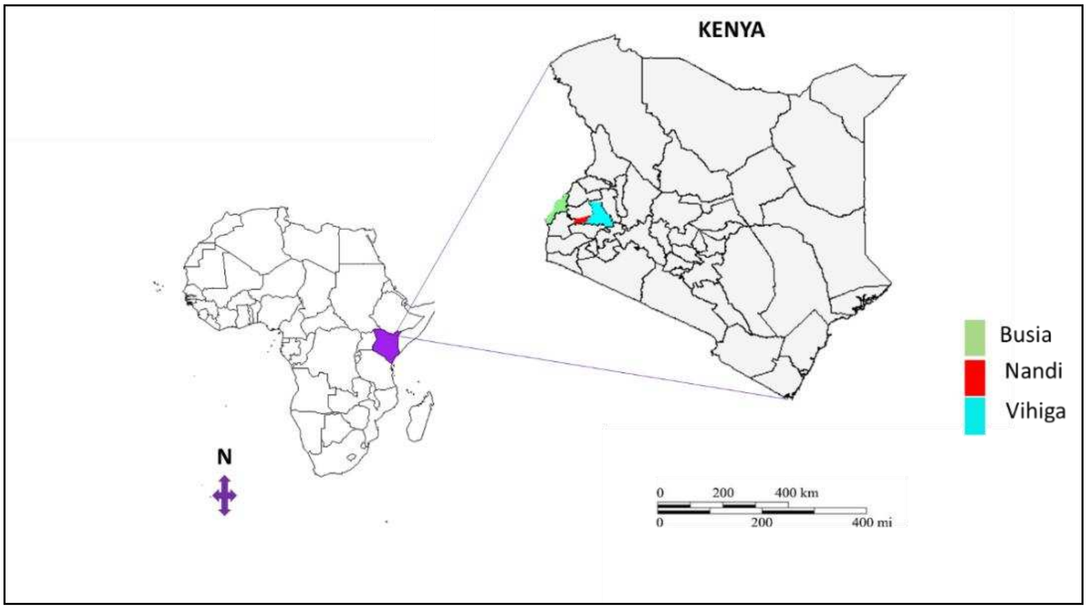

**Figure 4.1** The study sites Busia, Nandi and Vihiga counties in western Kenya.

**Table 4.1:** Climate and location data for three counties in western Kenya where farmers were surveyed to evaluate allocation of organic nutrient sources in smallholder farming communities.

| County | Location (Coordinates) | Altitude (m.a.s.l.) | Average Temperature (° C) | Average Annual Precipitation (mm) | Köppen-Geiger Climate Type* |
|---|---|---|---|---|---|
| Busia | 0° 26′ 0″ N, 34° 9′ 0″ E | 1165 | 22.4 | 1239 | Aw and Am-tropical savanna |
| Nandi | 0° 10′ 0″ N, 35° 9′ 0″ E | 1984 | 17.4 | 1551 | Cfa-Humid subtropical and Af-tropical rainforest |
| Vihiga | 0° 4′ 0″ N, 34° 40′ 0″ E | 1643 | 20.0 | 1921 | Af-tropical rainforest |

*Köppen-Geiger- Rohli, et al. (2015)

These counties also have different biophysical characteristics; for example, the soils in Nandi are typically ferralsols and acrisols, Vihiga is dominated by nitisols, while soils in Busia are typically acrisols (World Reference Base for Soil Resources, 1998). Although the soils differ in terms of SOM content and iron and aluminum oxide concentrations, they generally have similar challenges of poor soil fertility associated with declining SOM, low base saturation, low cation exchange capacity, high phosphorus fixation and high soil acidity (Sanchez, 2019). Major types of agricultural production in these counties include smallholders with subsistence and some cash crops (average < 1 ha land holding), mainly of maize (*Zea mays L.*) intercropped with common bean (*Phaseolus vulgaris*); crop-livestock production (dairy, beef, small ruminants and poultry); cash crop production (mainly tea, *Camellia sinensis)* in Nandi and Vihiga and sugarcane (*Sacharum officinarum*) in Busia (Sorre, 2017; Oduor et al., 2019; Tittonell et al., 2009). The integration of field crops, forage crops such as napier grass (*Pennisetum purpureum)* and horticultural crops such as vegetables and fruits are also common feature of these farms. The farms therefore produce a variety of organic resources from the crops grown and animals reared on farm, which have potential to return major nutrients (nitrogen, phosphorus, and potassium) in varying quantities to the fields (see Table 4.2).

**Table 4.2:** Nutrient content of selected organic inputs commonly produced and used on farm for crop production in western Kenya

| **Organic Input** | | **N** | **P** | ***K*** | ***Source*** |
|---|---|---|---|---|---|
| | | -----------------%-------------- | | | |
| Crop residues | Maize residues (*Zea mays*) | 0.89 | 0.08 | 2.78 | Okalebo et al., 2002 |
| | common bean residues (*Phaseolus vulgaris*) | 1.20 | 0.13 | 2.06 | |
| | Napier grass (*Pennisetum purpureum)* | 1.02 | 0.11 | 2.63 | |
| | Lablab *(Lablab purpureus*) prunnings | 1.31 | 0.33 | - | |
| Manures | Cattle manure fresh/composted | 1.12 | 0.30 | 2.38 | Lekasi et al., 2003 |
| | Poultry manure | 3.11 | 0.42 | 2.40 | Okalebo et al., 2002 |
| | Farmyard manure | 1.81 | 0.30 | 0.90 | *unpublished data* |
| | Compost | 1.34 | 0.20 | 1.82 | Okalebo et al., 2002 |
| Others | Biochar | 0.56 | 0.03 | 0.73 | *unpublished data* |
| | *Tithonia diversifolia* prunings | 3.50 | 0.37 | 4.10 | Jama et al., 2000 |

### 4.2.2 Study Approach

Data collection involved two main two activities: i) qualitative focus group discussions, and ii) a structured household survey.

### 4.2.3 Focus Group Discussions

Three focus group discussions were conducted in western Kenya, one in each county in July 2018 to understand the general ONS management practices in each community. Each focus group comprised a mixed group of 11 or 12 farmers, divided roughly equally by gender and a mix of age groups, but dominated by farmers more than 30 years old (~80%). A facilitator fluent in the local languages and familiar with agricultural practices in the region helped to facilitate the discussions. Notes were taken in local languages and later translated to English. The discussions (~ 2 hours each) were guided by the following themes: Crop and livestock production, soil fertility, organic residue management and trade-offs among ONS uses, and connections of farmers to sources of information on soil fertility management.

### 4.2.4 Household Surveys

In June of 2019 a structured and pre-coded survey was administered in local languages to smallholder farmers in the three communities mentioned above (following approval by the Colorado State University Institutional Review Board) to understand the drivers of management and allocation of ONS (see Table 4.3 and survey instrument in appendices).

About a third of farmers were sub-sampled from records of the Kenya Agricultural Livestock Research Organization (KALRO-Kibos) and two partner organizations working in the region (Appropriate Rural Development Agriculture Program and Avene Community Development Organization) using a stratified random sampling approach, where the farmers were stratified by gender of the household head. Each selected farmer also served as recruiter of two other farmers that were not involved in any project activities to reduce the bias from project involvement. Verbal consent was obtained from all farmers prior to beginning an interview (see - https://www.frontiersin.org/articles/10.3389/fsufs.2021.692981/full#supplementary-material). The total number of farmer interviews was 184 (Nandi=62, Busia= 60, and Vihiga=62) and the sample was ecologically and socioeconomically representative of the county zones. The surveys were collected on touchscreen tablets using an open data-kit survey on the KoBo Toolbox platform (Harvard Humanitarian Initiative, 2018) by four trained enumerators.

The survey addressed *predictor* variables for ONS allocation such as resource endowment, family demographics, and perceived soil fertility status and agroecological zone drivers (Table 4.3). In addition, information was collected on main residue types and quantities, as well as socio-cultural aspects related to contact with extension agents and local management norms. Meanwhile, survey *response* variables related to ONS and their role in nutrient management included the proportion of crop residues retained in the main plot and the proportion of cattle manure and poultry applied directly to the main plot (in composted and/or uncomposted forms - which gives insights on management of manure). Allocation to the main plot was taken as a key indicator of nutrient management with ONS since all farms had at least one main production field while not all had additional fields and previous studies have shown that ONS are applied preferentially to the main plot which makes it a benchmark for ONS management.

During the survey, a participatory modified 10-seed method (Jayakaran, 2002) was used to estimate the proportion of ONS allocated for different uses in relation to the total available. Farmers were given 10 beads representing the total ONS from a field or manure produced in that season. They were then asked to "allocate" the proportion of ONS they retained in-field, took to other fields or fed to livestock. This technique reduces recall bias over asking farmers to estimate actual amounts (Sawada et al., 2019; Wollburg et al. 2020).

**Table 4.3:** Dependent and predictor variables that were used for stepwise regression and stepwise multinomial logistic regression.

| Variable type | Group | Information asked from interviewees. |
|---|---|---|
| ***Predictor*** | Socio-economic | Livestock ownership (TLU* per household) |
| | | Area of main plot (ha) |
| | | Tenure of main plot (owned vs rented or shared) |
| | | Main source of labor (hired vs household members) |
| | | Food sufficiency (months $yr^{-1}$) ł |
| | | Crop residue main use (feed livestock/retain infield/compost/burning) |
| | | Mineral fertilizer use (Yes/No) |
| | | Family size |
| | | Education level of household head (none,primary,secondary,vocational/tertiary) |
| | | Gender of household head |
| | Socio-cultural | Number of trainings in soil fertility management attended (in the past 5 years) |
| | | Number of times the farmer has been visited by extension workers in the past year |
| | | Number of farm groups they belong to |
| | | Frequency of consulting other farmers on soil fertility management (contacts per season) |
| | | Adherence to perceived social norms of crop residue management (Yes/No) |
| | Environmental | Location (agroecological zones) |
| | | Perceived soil fertility status of main vs. secondary cropping plots ƛ |
| ***Response*** | Allocation and use of organic inputs to the main plotϮ | % of crop residues retained (continuous) |
| | | % of cattle manure (composted, uncomposted and combined) applied (continuous)** |
| | | % of poultry manure applied in-field (continuous) |
| | | Main use of crop residues (categorical) |

*Livestock ownership was converted to Tropical Livestock Units (TLU) by multiplying the number of livestock owned by a factor (cattle=0.7, sheep=0.1, goats=0.1 and poultry=0.01).

ł Farmers where asked how many months in a year that they felt they had enough food to feed their household comfortably with 3 meals a day.

ƛ Soil fertility status refers to the main plot vs the secondary plot according to the farmer's perception, main plot usually perceived as more fertile

Ϯ The study concentrated on the allocation of ONS to the main plot because half of the farmers did not have a secondary plot and of those that had, less than half applied any ONS to it.

** We looked at 3 dependent variables for cattle manure allocation as is normally done in the 3 areas i) adding cattle manure to compost and/ or composting it before applying to the field (composted cattle manure) and ii) applying it to the field directly without composting (uncomposted cattle manure) iii) combining the composted and uncomposted cattle manure (combined cattle manure).

### 4.2.5 Study population characteristics

The study population consisted of 75 % of male headed households, but most of the respondents (54 %) were women, i.e., the spouse of the household head (Table 4.3). Most of the household heads were moderately to well educated (46 % with some primary education and 47% with secondary education or beyond), while 7 % reported no formal education. The households were generally large, with 69 % having at least 5 people. Roughly 55 % of the households reported being food secure for at least 8 months. Most households had at least two sources of income, but farming was the main livelihood for all households surveyed. Trade and business (34% or respondents) and remittances (34% of respondents) were mentioned as additional sources of income. Only 29 % of the households had a formally employed household head (i.e. with an off-farm job).

**Table 4.4**: Household demographic information and farm characteristics of smallholder farmers interviewed in Nandi, Busia and Vihiga counties in western Kenya in June 2019.

| Location | Busia<br>*(n=60)* | Nandi<br>*(n=62)* | Vihiga<br>*(n=62)* |
|---|---|---|---|
| | -------- number of households per category ------ | | |
| **Gender of household head** | | | |
| Female | 13 | 19 | 15 |
| Male | 47 | 43 | 48 |
| **Household size (no. of members)** | | | |
| 2 or less | 2 | 1 | 1 |
| 2-5 | 12 | 15 | 18 |
| 5-9 | 35 | 33 | 40 |
| >10 | 11 | 13 | 4 |
| **Food sufficiency (months)*** | | | |
| 12 | 16 | 10 | 13 |
| 8 to 11 | 26 | 18 | 18 |
| 5 to 7 | 9 | 8 | 15 |
| <5 | 9 | 26 | 17 |
| **Livelihood strategies** | | | |
| Farming | 60 | 60 | 62 |
| Formal employment (off farm) | 9 | 6 | 11 |
| Trade and craft | 15 | 21 | 27 |
| Aid (government or NGO) | 2 | 1 | 0 |
| Others e.g. rentals | 3 | 4 | 1 |
| **Education of household head** | | | |
| No formal education | 7 | 3 | 4 |
| Primary education | 26 | 31 | 27 |
| Secondary (up to high school) | 20 | 22 | 29 |
| Tertiary and beyond | 7 | 6 | 3 |
| **Mineral fertilizer use** | | | |
| No | 10 | 7 | 6 |
| Yes | 50 | 55 | 56 |
| **Tenure of main plot** | | | |
| Owned | 49 | 55 | 49 |
| Rented/shared | 11 | 7 | 13 |
| **Farm characteristics** *mean (se)* | | | |
| Livestock ownership (TLU) ɫ | 2.48 (0.3) | 1.64 (0.2) | 1.51 (0.2) |
| Area of main plot (ha) | 0.52 (0.07) | 0.56 (0.07) | 0.30 (0.03) |

* Farmers were asked how many months in a year that they felt they had enough food to feed their household comfortably with 3 meals a day.

ɫ Livestock ownership was converted to Tropical Livestock Units (TLU) by multiplying the number of livestock owned by a factor (cattle=0.7, sheep=0.1, goats=0.1 and poultry=0.01).

### 4.2.6 Estimation of ONS produced on farm

Average total organic inputs were estimated for maize crop yields from farmer reported maize yield (Mg ha$^{-1}$) assuming a harvest index of 0.44 (Dawadi and Sah, 2012). Cattle and poultry manure produced in the main season (Long rainy season March to May) was estimated using the formula:

$$TM = ME * days * No.animals * (1 - m)$$

where TM is the gross total cattle and poultry manure (kg DM season$^{-1}$) produced, and estimated without removing possible losses in storage, feeding and respiration, ME is the amount of manure excreted by each animal (i.e. cattle = ~20 kg day$^{-1}$ animal$^{-1}$ (Nennich et al., 2005)) and poultry = ~0.13 kg day$^{-1}$ animal$^{-1}$ (Williams et al., 1999), days is the estimated length of the rainy season in days (i.e. 120 days), No. of cattle is the number of cattle or poultry a farmer has, and m is the estimated moisture content of the manures.

### 4.2.7 Data Handling and Statistical analysis

The data were downloaded from KoBo Toolbox, cleaned, and standardized as needed. For example, livestock ownership was converted to Tropical Livestock units (TLU) by multiplying the number of livestock owned by a factor (cattle=0.7, sheep=0.1, goats=0.1 and poultry=0.01) according to Chilonda and Otte (2006). Adherence to social norms of crop residue management was determined by comparing responses of what the farmer does against what they think is normally done with residues or manures in their area.

All data analysis was done in R v 3.6.2 (R Core Team, 2019), where the variables used as predictors (Table 4) in all the models were selected using a PCAmix algorithm for mixed data sets which combines a principal component analysis (PCA) for continuous variables and multiple correspondence analysis for categorical variables in ClustofVar package (Chavent et al., 2014) to reduce redundant and highly correlated variables. As such, variables with squared loadings of $< 0.3$ were dropped from the analysis as suggested by Hair et al. (1998). Location and gender were retained as they have been shown to be important predictors in similar studies (e.g. Kristjanson, 2017; Liu et al. 2018). Factors explaining variability in the proportion of crop residues retained in-field and manure used (cattle and poultry) were determined using stepwise regression based on Akaike Information criteria (AIC) with the selected model having the smallest AIC value (Akaike, 1987). Data was tested for regression assumptions of normality, homogeneity of variance, linearity and independence. Differences in ONS inputs applied in the main plot and secondary field were determined using t-tests. A stepwise multinomial logistic regression model was used to determine factors important in explaining variability in the main use of crop residues using the package mlogit (Croissant, 2020). The model was tested for multicollinearity using the generalized variance inflation factor (GVIF) which was $<2$ (Fox and Monette, 1992) as well as other regression assumptions. Differences in ONS management between locations and characteristics were determined using ANOVA and fisher's exact tests. Tukey honestly significant difference (HSD) at $p<0.05$ was used for pairwise comparisons between groups.

### 4.2.6 Development of farmer typologies for ONS management

Types for ONS management were developed using hypothesis-based typology formation (Alvarez et al., 2018), where variables selected depend on the objectives of classification. The variables that were considered important in explaining variability in ONS management as selected by PCAmix and subsequently stepwise regression above were used as basis for classification. Fuzzy k-means classification as described by Salasya and Stoorvogel (2010) using the fclust package in R (Ferraro et al., 2019) was used to form clusters according to minimized Euclidean distances within farm typology groups. These farm types were then characterized by testing for differences in ONS allocation and social connections related to ONS information, by using ANOVA and Fisher's exact tests where a $p < 0.05$ was considered significant. Between-Class PCA (BCA) was used to to determine possible group distinction following characterization into typologies using the ade4 package (Bougeard and Dray, 2018) and overall significance differences among classes determined with a post hoc Monte-Carlo test.

## 4.3 RESULTS

### 4.3.1 Focus group discussions

Relevant quotes from the focus group discussions illustrate broadly how farmers consider the themes of crop residue and manure allocation, gender responsibilities and trade-offs in ONS management (Table 4.5). Overall, the farmers in Nandi and Vihiga, and to a lesser extent Busia, placed value on feeding the livestock over returning residues to the plots (Quotes 1 and 2) because they prioritize livestock and the resulting value from selling milk (Quotes 8 and 9). Other tradeoffs in residue allocation result from alternative household uses such as burning of legume residues for salt (a special ash used in the cooking of traditional vegetables and meat preservation; Quotes 6 and 7). Management of ONS is determined by gender, especially for legumes, where female members of the household were responsible for management of crop residues (Quotes 5 and 6), while a few farmers stated that maize stalks are mainly managed by male members of the household (Quote 4). In Busia, older farmers preferred to leave residues in the plot or sell them in situ to the few farmers without their own, as they see it as laborious to carry the stalks home (Quote 10).

**Table 4. 5:** Farmer quotes on organic nutrient source management, responsibilities and trade-offs following focus group discussions in Nandi, Vihiga and Busia counties in western Kenya in July 2018.

| Theme | Focus Group Quotes Exploring the Theme |
|---|---|
| Crop residue and manure allocation | 1. "We believe in letting the farm feed the cattle and the cattle feed the farm" Nandi farmer<br>2. "I prefer feeding our livestock first and what remains I can take to the field" Vihiga farmer<br>3. "Some of us may consider applying manure only in sections that have shown good yield potentials and ignore other sections" |
| Gender responsibilities in ONS management | 4. "The decision on how maize stalks are used is usually made by the male members of the household as they value their livestock and believe that all cattle belong to them"<br>5. "The decision to burn legume residues is usually made by female members of the household"<br>6. "Female farmers determine the use of bean residues, and they burn them to make salt" |
| Trade-offs in ONS management | 7. "We burn legume residues for cooking traditional vegetables or we can sell the ash for 200 shillings/ 20kg bag."<br>8. "I can exchange maize stalks for milk"<br>9. "I can fetch more money from selling milk, so I prefer giving the residues to my livestock"<br>10. "There are farmers who are very old and cannot carry the residues home to feed animals and therefore leave them on the farm or sell them, a bundle of maize stalks sells for 50 shilling (equivalent to 50 cents United States Dollars)" |

### 4.3.2 General management of organic nutrient sources

The most fertile plot according to the farmers' perception was defined as the main plot and the less fertile plot was defined as the secondary plot. About half of the of the households surveyed (56 %) had a secondary plot in addition to the main plot, with the others just managing a single plot. There was large variability in plot size for both main and secondary plots, but landholding was generally small, with an average plot size of < 0.5 ha for both plot types (Table 4.6). Most plots were owned by the household, but a higher proportion of the secondary plots were shared or rented than for main plots. Plot designation influenced management, such that the main plot used intercropping or mixed cropping systems and the majority had ONS applied to them (Table 4.6). In contrast, there were more secondary plots that were sole cropped (46 %) or that were left fallow

(14 %) compared with intercropping/mixed cropping (40 %). Farmer reported maize yields for the 2018 long rainy season were significantly higher in the main plots than the secondary fields, while beans yields were marginally higher in the secondary plot (Table 4.6).

**Table 4.6:** Characterization of farming systems and organic input use in the main plots vs. secondary plots in smallholder systems from western Kenya. P-values for differences between means of the main and secondary plots are shown in the far-right column.

| | | **Main plot *(n=184)*** | **Secondary plot *(n=102)*** | **p-value** |
|---|---|---|---|---|
| Plot size (ha) *mean (se)* | | 0.45 (0.48) | 0.27 (0.29) | *0.001** |
| Tenure | Owned | 83% | 73% | |
| | Rented/Shared | 17% | 27% | 0.001* |
| Main farming system | Mixed/intercropping | 75% | 40% | |
| | Sole cropping | 24% | 46% | *0.004ł* |
| | Fallow | 1% | 14% | |
| Organic input use in plot | Yes | 78% | 44 % | *0.005ł* |
| | No | 22% | 56% | |
| Average yield-2018 long rainy season (Mg ha$^{-1}$) | Maize | 1.03 | 0.44 | *0.001** |
| | Beans | 0.44 | 0.46 | *0.04** |

* p values for t-tests between the main plot and secondary plot means

ł p-values for Fisher's Exact tests for differences in proportion between the main and secondary plots variable levels.

Consistent with our focus group findings, maize crop residues produced from the plots were mainly fed to livestock (by 53 % of households) or retained in-field (by 33 % of households). A few farmers (8 %) added the residues to compost and 8 % of households had no residues at all due to crop failure. Other uses of crop residues such as burning of legume residues for salt (76 % of households that grew legumes) or burning in-field in the case of cereal residues (2 %) were noted. Regarding composting, 61 % of farmers owned a compost or farmyard manure pile composed of all their manure or a selection of manure, crop residues, ash, kitchen waste, while 39 % had no compost pile of any form. Other ONS such as biochar and *Tithonia diversifolia* were mentioned by only 5 % and 7 % of farmers, respectively, who added these as well as leaf litter from the nearby trees and forest to their compost/farmyard manure.

### 4.3.3 Gender and organic nutrient source management

The general allocation and management responsibility of organic resources by gender depended on the type of ONS (Fig. 4.2). Generally, more households had their ONS managed by female members of the household compared males. Responsibility between genders differed slightly with animal manure, maize residues, and compost/farmyard management (Fig. 4.2). However, management of legume residues was mainly the responsibility of the female household members (57 % female vs. 23 % males: n = 160 households). Allocation of poultry manure to the main plot was significantly higher in male headed households (mean± standard error: 55 ± 6.7 %; n=137) than female headed households (39 ± 3.9 %; n= 46).

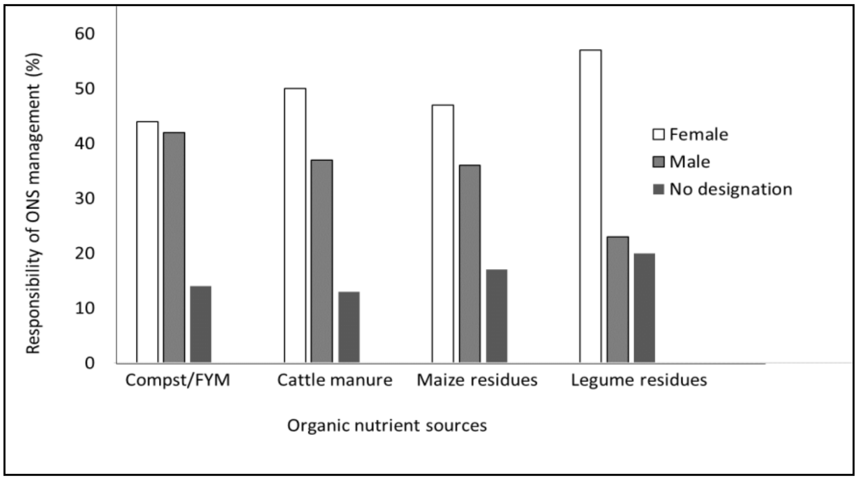

**Figure 4.2:** Management responsibility of organic nutrient sources separated by gender in households of Busia, Nandi and Vihiga counties in western Kenya. Number of households producing compost/Farmyard manure(FYM)=113 ; number of households with Cattle manure=167; number of households with maize residues=180; number of households with legume residues =160.

### 4.3.4 Zone to zone variation in organic nutrient source allocation

The main use of crop residues differed by location (p<0.001), where the number of farmers in Busia who retained their crop residues in-field was 3 and 4 times higher than in Vihiga and Nandi respectively (Fig. 4.3). Farmers in Nandi and Vihiga were more likely to feed crop residues to livestock than retain them in the field.

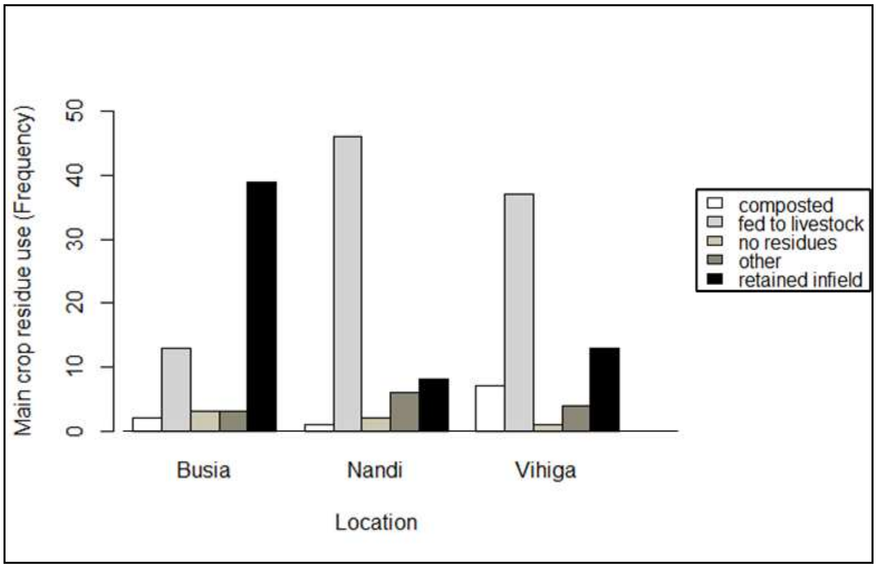

**Figure 4.3**: Frequency of the farmers in Busia, Nandi and Vihiga counties in western Kenya who allocate crop residues produced from their main plot for to a variety of different uses.

The proportion of crop residues allocated to the main plot versus other fates also differed between locations (p<0.001; Table 4.7). Crop residues retained in the main plot were significantly influenced by location, where farmers in Busia retained on average twice the amount of residues in the main plot (67.33 ± 4.53 %) plot than that observed in Nandi and Vihiga ( 39.9 ± 3.5 %; 29.51 ± 3.73 %). There were also significant differences in the proportion of composted cattle manure allocated to the main plot in the three locations (p=0.01; Table 4.7) with farmers in Busia and Vihiga allocating a higher proportion of the manure produced to the main plot ( 51.3 ± 5.4 % ,49.8 ± 5.3 % vs 32.3 ± 5.3 % in Busia,Vihiga and Nandi respectively).

**Table 4.7:** Farm-level predictors selected using a stepwise regression that explain variation in the proportion of crop residues retained, cattle and poultry manure applied to the main plot in Nandi, Vihiga and Busia counties of western Kenya. Data was collected from 184 households in June of 2019.

| Dependent variable | Predictor variable in final model* | $\eta^2$ | p-value |
|---|---|---|---|
| Proportion of **crop residue** left in main plot | Location | 0.24 | <0.001 |
| | Adherence to norms (residue) | 0.04 | 0.04 |
| | Tenure (main plot) | 0.04 | 0.002 |
| | Area of main plot (ha) | 0.02 | ns |
| Proportion of **composted cattle manure** allocated for use in main plot | Location | 0.05 | 0.01 |
| | Number of animals (TLU) | 0.06 | 0.001 |
| | Extension visits | 0.08 | 0.002 |
| | Area of main plot (ha) | | ns |
| Proportion of **uncomposted cattle manure** allocated for use in main plot | Area of main plot (ha) | 0.02 | 0.03 |
| | Labor (hired vs household members) | 0.08 | ns |
| | Months secure ł | 0.11 | 0.002 |
| | Adherence to norms (of composting) | 0.05 | 0.04 |
| Proportion of **cattle manure (composted plus uncomposted)** allocated for use in main plot | Number of animals (TLU household$^{-1}$) | 0.17 | <0.001 |
| | Labor (hired vs household members) | 0.04 | 0.08 |
| | Education | 0.04 | 0.07 |
| | Area of main plot (ha) | 0.05 | 0.02 |
| Proportion of **poultry manure** allocated for use in main plot | Gender | 0.02 | 0.04 |
| | Area of main plot (ha) | 0.02 | 0.09 |

*Are predictor variables selected in the final model following stepwise regression analysis. TLU are Tropical Livestock Units (TLU). ł Farmers were asked how many months in a year that they felt they had enough food to feed their household comfortably with 3 meals a day. $\eta^2$ is the proportion of variance explained by each predictor variable; ns means not significant.

### 4.3.5 Resource endowment factors

A variety of farm resource indicators influenced allocation of ONS to the main plot as an indicator of nutrient management strategies (Table 4.7). For example, farms with greater numbers of livestock (TLU) allocated significantly more composted and combined cattle manure to the main plot ($R^2$=0.08; p=0.001 and $R^2$=0.14; p<0.001 respectively) than those with fewer livestock. Households that were more food secure (i.e., those that indicated having enough to feed their families comfortably 3 meals a day for 12 months) applied significantly less uncomposted cattle manure (average proportion allocated to the main plot=22 % ± 5.3; n=33) compared to households that were less food secure (average proportion allocated to the main plot 51 % ± 7.33; n=36; p =

0.02; Table 4.7). Regarding land tenure, farmers who rented or shared plots retained significantly more residues (owned 39.28 % ± 2.76 vs shared/rented 59.03 % ± 6.3: t-test p = 0.006) than those who owned their main plots. Area of main plot influenced manure applied, in that plot size decreased marginally with increase in cattle and poultry manure allocated.

### 4.3.6 Socio-cultural factors as drivers of ONS management

Adherence to social norms helped to explain some of the variability in ONS management (Table 4.7). However, adherence to norms of crop residue management appeared to depend on location (adherence to norms by location interaction: p = 0.04; Table 4.8). Overall, farmers who indicated adherence to social norms of crop residue management in Vihiga retained significantly less residues in the main plot than those who did not adhere to norms, which reflects the more common practice of retaining few residues in-fields there, in favor of feeding to livestock. The few farmers who did not adhere to perceived social norms of crop residue management in the three locations explored other options of crop residue management namely composting (5 % of farmers) and other uses such as burning, selling main and transferring to other plots (7 % of farmers).

The proportion of uncomposted cattle manure applied to the main plot was significantly related to adherence to social norms of composting (p=0.04; Table 4.7). Households that did not adhere to social norms of composting (i.e., not composting manure before application) applied more uncomposted cattle manure (average proportion applied to main plot 52 % ±10.6; n=19) compared to those that were not sure of composting norms (average proportion applied to main plot:36 % ±4.9; n=64) and those who adhered composting norms (average proportion applied to main plot: 25 % ±4.7; n=62).

**Table 4.8**: Percentage of total crop residues retained, and total uncomposted cattle manure applied to the main plot as influenced by adherence to social norms in three counties of western Kenya (Nandi n = 62 and Vihiga n = 62; Busia n = 60). Means connected by the same letter are not significantly different using Tukey's HSD pairwise comparisons. Numbers in parenthesis are the standard error of the mean.

| | **Location** | **Crop residues retained** | | | **Uncomposted cattle manure** | | |
|---|---|---|---|---|---|---|---|
| | | *-----------------------% average proportion applied to main plot -------------* | | | | | |
| Adherence to norms of ONS management | | No | Yes | Not Sure | No | Yes | Not Sure |
| | Busia | 74.4<br>(6.75)$^{d}$ | 65.2<br>(6.73)$^{cd}$ | 50.0<br>(13.09)$^{abcd}$ | 57.8<br>(12.94)$^{b}$ | 18.3<br>(8.10)$^{a}$ | 31.9<br>(9.71)$^{ab}$ |
| | Nandi | 27.7<br>(8.06)$^{ab}$ | 33.5<br>(3.68)$^{ab}$ | | 37.8<br>(12.94)$^{b}$ | 40.0<br>(11.71)$^{a}$ | 42.4<br>(7.21)$^{ab}$ |
| | Vihiga | 45.6<br>(7.07)$^{bc}$ | 19.1<br>(3.04)$^{a}$ | | 100<br>(38.8)$^{b}$ | 26.2<br>(7.21)$^{a}$ | 26.7<br>(8.47)$^{ab}$ |
| | *p -values* | *Adherence: p=0.003*<br>*Location: p=<0.001*<br>*Adherence x Location: p=0.04* | | | *Adherence: p=0.04*<br>*Location: ns*<br>*Adherence x Location: ns* | | |

Extension visits were significantly correlated with the proportion of composted cattle manure allocated to the main plot (p=0.002; Table 4.7). Overall, farmers who had never been visited by extension (99 out of 184 farmers) allocated approximately 1.5 times less composted cattle manure than those who had interacted with extension at least one or more times. The same trend was noted when the data was disaggregated into counties (Fig. 4.4).

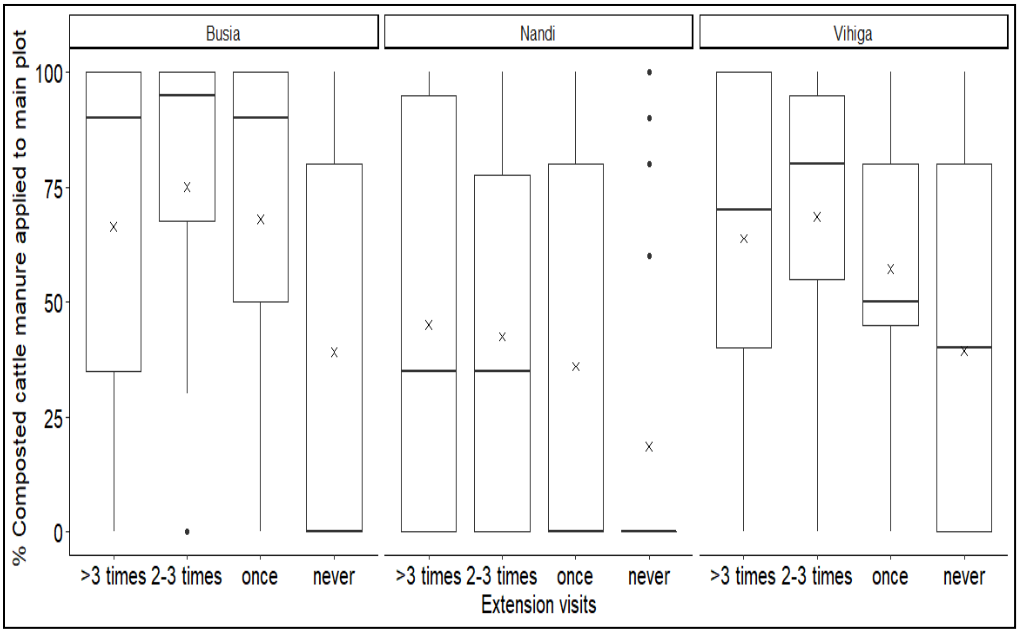

**Figure 4.4:** The percentage of composted cattle manure applied in farmers' main plot as influenced by the number of interactions with extension agents in Busia, Nandi and Vihiga counties in western Kenya. Box plots show the spread the data points for each group, while the mid-line represents the median of each group and x indicates the group mean.

### 4.3.7 Organic nutrient sources in relation to farm typology

There were six ONS management clusters formed from the surveyed farms using fuzzy k-means classification (silhouette width=0.60, lowest average membership degree=0.88). These were then further grouped into four types by merging two of the pairs of clusters that had the shortest Euclidean distance (Table 4.9). The majority of the farmers (72%) were in the less resource endowed and less connected farm Types 3 (n=92) and 4 (n=44).

**Table 4.9:** Constructed farm typologies using fuzzy k-means classification for organic nutrient sources allocation across 184 farming households Nandi, Vihiga and Busia counties in western Kenya. Descriptions are provided for each type based on mean values of farm resource endowment, adherence to norms of organic nutrient sources practices, and connectedness to information sources for organic nutrient sources management practices.

| Farm type | *n* | Description |
|---|---|---|
| 1 | 28 | **Resource endowed**<br>Farmers with livestock in forms of cattle and poultry (Tropical Livestock Units-TLU >3); have relatively larger pieces of plots(>0.4 ha). Some farmers have good interactions with extension over 3 times in a year, but some were never visited by any extension member. They tend not to be clearly influenced by social norms of crop residue management. |
| 2 | 19 | **Non-adherent and well connected**<br>Farmers with livestock ownership of TLU between 1.5 and 3. They have smaller plot size area of the main plot about, 0.4 ha. The farmers tend not to adhere strongly to social norms of crop residue management and have had frequent interactions with extension (more than two times the previous year) |
| 3 | 93 | **Adherent and less connected**<br>Farmers with few to no livestock (average TLU of <1.5) The land sizes are very small (<0.4 ha). They adhere strongly to social norms of management, and most have little to no interaction with extension workers. |
| 4 | 44 | **Least resource endowed**<br>Farmers with few to no livestock (average TLU of <1) The land sizes are very small (<0.4 ha). They do not adhere strongly to social norms of management, and most have never been visited by extension workers before. |

When examining differences between the farm types, there were no significant differences in the average total maize residues produced; however, Type 1 (Resource endowed) farmers produced the highest yield (1.04 Mg ha$^{-1}$) and Type 4 (Least resource endowed) farmers the lowest (Table 10). Similarly, farm type had no influence on the proportion of maize residue retained to the main plot, but Type 1 and Type 4 farmers retained a higher proportion of residues infield while Type 2 (Non-adherent and well connected) and Type 3 (Adherent and less connected) farmers retained less residues infield.

Type 1 farmers had significantly more estimated manure production per season (1,639 kg season$^{-1}$) compared to all the other farmers (Table 4.10). The proportion of composted cattle manure and combined cattle manure applied to the main plot did not significantly differ with type but followed the order Type 3>Type 4≥Type 1> Type 2 and Type 2>Type 3>Type 1≥ Type 4 respectively. However, the proportion of uncomposted cattle manure was significantly higher (p=0.04) in Type 2 farmers, followed by Type 4 and Type 1 and 3 farmers had the least proportion allocated to their main plot (Table 4.10).

Small quantities of poultry manure were produced by farmers and did not differ significantly among types (Table 4.10). Nevertheless, there were significant differences in percentage of poultry manure applied in the main plot (p = 0.04), in which Type 2 and 4 farmers had higher average proportions allocated to the field (mean 62.1 % and 60.2 %, respectively) than Type 3 and Type 4 farmers (mean = 51.6 and 31 %, respectively).

There were significant differences in the socio-cultural interactions of farmers by farm type with regards to obtaining information on soil fertility and ONS management. Training of farmers in areas of soil fertility (in workshops or field days) and ONS management was significantly different with farm type (Fisher's exact test p=0.01). Type 2 farmers were the most trained with at least 89 % of farmers having received some form of training. This was followed with type 1 (57%) and type 3 (54%) farmers. Type 4 farmers were the least trained with just 41% of them having received formal training at least once since they started farming.

Belonging to farmer groups (where farmers from the same community come together to learn from each other and or pool produce for marketing amongst other reasons) was significantly different among farmer types (Fisher's exact test, p=0.02). Type 1 and 2 farmers were more likely to belong to farmer groups, with 61% and 88%, respectively belonging to at least one farmer group. Most Type 4 farmers (66%) did not belong to any farmer group. 52 % of Type 3 farmers belonged to at least one farmer group.

Consultation with other farmers on issues concerning soil fertility and organic nutrient sources management was significantly different with type (Fisher's exact test p= 0.03). Type 2 farmers were the most interactive, with at least 56 % of the farmers having consulted other farmers at least once in the season. This was followed by Type 3 farmers (36%), Type 1 farmers (29%) and lastly only 13 % of Type 4 farmers consulted other farmers at least once in the season.

Between class analysis (BCA) showed that the first two axes of variation encompassed 85 % of the variability in the chosen set of descriptor variables for farms (Fig. 5), and highly significant differences among the four farmer types (Monte-Carlo test p-value=0.001). Nevertheless, there was some overlap between farm types (Fig. 4.5), such that farm Type 1 is clearly separated from the other three types in that on average they have more livestock and a larger area of land. There is a subtle distinction between Types 3 and 4, as Type 3 are more adherent to residue management and are bit more likely to be in Nandi than Type 4. Finally, Type 4 allocate more poultry/manure than other types.

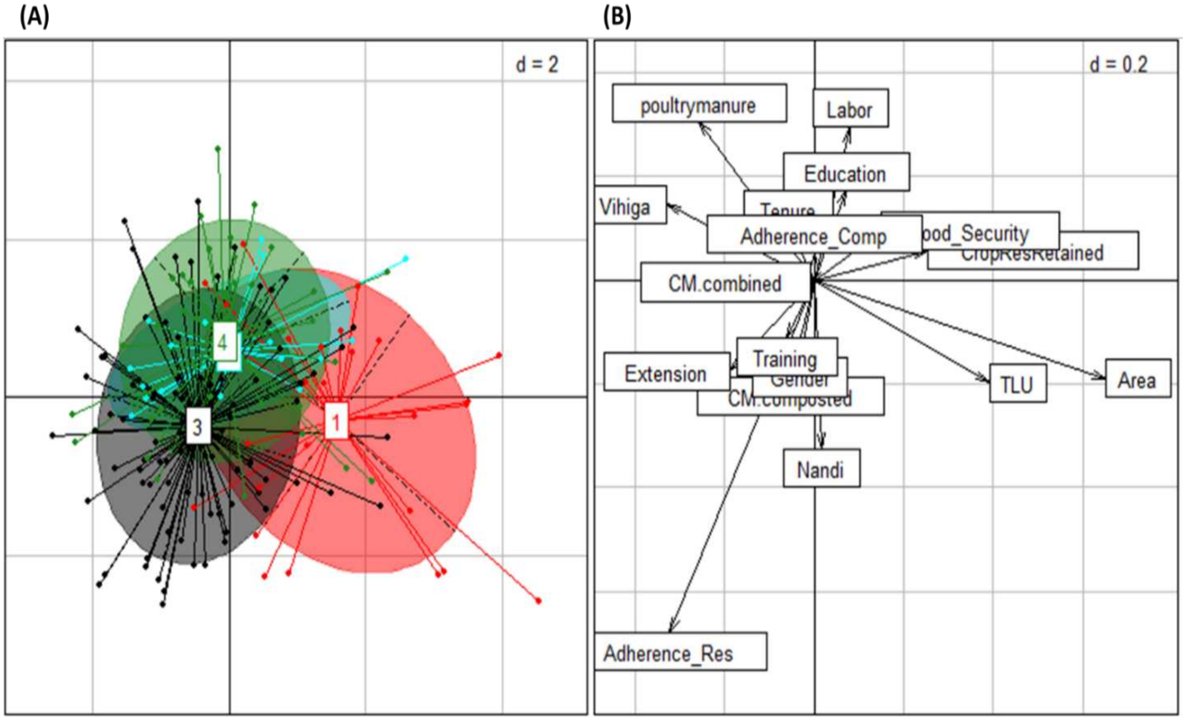

**Figure 4.5:** Between class analysis (BCA) showing group separation ((A) group classes and (B) arrow linking points to origin) for constructed farm typologies in organic nutrient sources management in three counties in western Kenya. The groups 1 to 4 are constructed farmer types of ONS management (see Table 9). TLU is Tropical Livestock Units; Area is area of main plot; Nandi/Vihiga are counties in western Kenya; Education is the education level of household head; CM.combined, CM.composted and CropResRetained represent the proportion of cattle manure not composted and composted and crop residues that were allocated to main plot, respectively; Adherence_Res and Adherence_Comp refers to adherence to social norms of crop residue and compost management, respectively; Extension is the number of times a farmer had interactions with extension agents in the previous year; Food-Security refers to how many months in a year that farmers felt they had enough food to feed their household comfortably with 3 meals a day. Labor represents main source of farm labor (hired /household members). Training is the number of formal trainings in soil fertility management attended by the farmer in the past 5 years.

**Table 4.10:** Mean total organic inputs by farm type produced by farming households (n = 184) during a typical long rainy season in western Kenya. Values are reported for the proportion of crop residues retained, as well as cattle manure (composted and uncomposted) and poultry manure applied to the main plot. Numbers in parentheses are the standard error of mean. P-values are report difference between the different farming household typologies, while means followed by different letters are significantly different from each other according to Tukey's HSD pairwise comparisons.

| | | **Organic inputs** | | | **Proportion allocated to main plot** | | | |
|---|---|---|---|---|---|---|---|---|
| Farm type | Average size of main plot | Crop Residues (maize) | Cattle manure | Poultry manure | Crop residues (maize) | Composted Cattle Manure | Uncomposted Cattle manure | Poultry manure |
| | *-----ha-----* | *--Mg ha$^{-1}$ long season$^{-1}$ -------* | *--------kg DM farm$^{-1}$ long season$^{-1}$ -------------* | | *----% of total organic resources allocated to the main plot ---* | | | |
| 1 | 0.98 (0.16)$^{b}$ | 1.04 (0.11) | 1 639 (203)$^{a}$ | 174 (37.1) | 54.8 (6.48) | 42.4 (7.94) | 26.5 (7.62)$^{ab}$ | 31.0 (8.48)$^{a}$ |
| 2 | 0.47 (0.08)$^{a}$ | 0.86 (0.18) | 740 (257)$^{b}$ | 158 (38.1) | 37.4 (8.00) | 31.6 (9.8) | 58.1 (9.91)$^{b}$ | 62.1 (10.48)$^{ab}$ |
| 3 | 0.35 (0.03)$^{a}$ | 0.75 (0.75) | 794 (113)$^{b}$ | 106 (18.9) | 38.3 (93.62) | 48.3 (4.43) | 28.5 (4.51)$^{a}$ | 51.1 (4.73)$^{ab}$ |
| 4 | 0.35 (0.05)$^{a}$ | 0.68(0.14) | 745 (164)$^{b}$ | 85 (26.6) | 45.9 (5.26) | 42.7 (6.65) | 35.9 (6.86)$^{ab}$ | 60.2 (6.88)$^{b}$ |
| *p-value* | *<0.001* | *ns* | *0.002* | *ns* | *ns* | *ns* | *0.04* | *0.04* |

## 4.4 Discussion

Our results showed that the main determinants of ONS management in these mixed crop-livestock systems of western Kenya were environmental (agroecological zone context and perceived soil fertility), resource endowment (TLU, area, months food secure and tenure of plot) as well as socio-cultural (adherence to social norms and interaction with extension). Additionally, we note that responsibilities in management and allocation of ONS were gendered for some resources (e.g. legume residues), and also show a general trend of women overseeing most ONS. These findings thus lend support to existing frameworks on allocation of ONS management in smallholder systems that have placed emphasis on resource endowment as a major determinant of ONS management (Ayaji et al., 2007; Mugwe et al., 2009; Andrews et al., 2013), but also indicate some divergent or interesting additional patterns in allocation of ONS in smallholder farms of this region.

### 4.4.1 Household members, gender, and management of ONS

In most households, female members were the ones responsible for managing and allocating resources such as compost, maize residues, and animal manures. Management of legume residues, moreover, was clearly a female household member's responsibility (Quotes 4, 5 and 6; Table 5; Fig. 2). Women manage most of the growing and post-production handling of legume crops as they are generally considered a 'woman's crop' due to lower value compared to maize (Ferguson, 1994). Women farmers have been noted to have an interest in diversifying cropping systems with legumes because of their nutritional value, since they are typically responsible for preparing meals for families (Snapp et al., 2019). This generally aligns with other studies showing how women's role of providing and making food for the family influences their choices regarding use of household resources available to them (e.g., DeVault 1994). This can also explain the choice of burning of residues over other uses such as retaining the residues infield, since legume residues are also used for the production of 'salt' that can be used to preserve meat for traditional meals, or it can be used as a feed supplement for cattle. Clearly then, understanding gender factors that influence the fate of legume residues is crucial, especially in light of the fact that these residues are often promoted to improve soil health and crop yields (Ojiem et al., 2014; Smith et al., 2016). Further, we note that engaging only with males in households regarding the benefits or challenges of legume residue management is likely to be far less effective than engaging with women. Overall, this finding shows how use of legumes, and alternative uses including as ash for salt, has important economic and cultural value, and this should be considered as a determinant of ONS allocation.

### 4.4.2 Spatial variability at different scales: Zone to zone and within-farm variability of ONS management

Agroecological factors or what Liu et al. (2018) called 'macro factors' that form the common management backdrop for a large number of farmers in one region versus another, often influence the allocation of organic resources within a smallholder farm. In our study, it is likely that the strong effect of location on ONS management was mediated by a range of climatic conditions and soils which determine the type of farming systems possible, and in turn, determines the type and amount of organic resources that are produced on a farm (Rusinamhodzi et al., 2016; Pedzisa et al., 2015). In our study, Nandi (at high elevation and medium rainfall) had a lower proportion of residues retained in-field than Busia (at low elevation and lower rainfall). This is likely related to the fact that Nandi is located at higher altitudes and more intensive, zero-grazing dairy farming is more common due to a climate that better supports dairy production. As such, the farmers there require feed to be harvested and carried from the fields to the cattle pens after harvest to supplement animal feed. In Busia, however, it is the common practice to retain crop residues in the field since animals are mostly open grazed rather than pen fed. Similar to Nandi, Vihiga (medium elevation, high rainfall) is higher in elevation and has more intensive farming systems than in Busia but retains slightly less residues in-field.

In addition to this zone-level variation, within farm spatial gradients also affected nutrient management, by which farmers prioritized ONS allocation to main plots over secondary plots. While the less productive plots do receive their own residues, they tend to have lower productivity and thus lower residue biomass inputs than the main plots. Such management gradients likely lead to heterogeneity in soil fertility within farming systems, where the plots closer to the homestead (usually the main plot for security reasons, ease of manure or compost application, or other conveniences) typically have higher fertility. This aligns well to other studies in which farmers concentrate their organic resources on main or favored fields, even if it might be more productive to distribute a greater proportion of their ONS to less productive fields (Mtambanengwe and Mapfumo 2005; Masvaya et al 2010, Giller et al., 2011, Tittonell et al., 2005). The type of crops grown in the plot also influences the proportion of residues retained or taken away from that plot. For example, since legumes are mostly grown in the outfields/secondary plots, and legume residues are burnt off field to be used in the homestead for salt or cattle licks, they often do not contribute much to soil fertility save for a minor contribution through root biomass.

### 4.4.3 Resource endowment factors affecting ONS management.

Farmer resource endowment proxies, namely livestock ownership (TLU), food security and to a lesser extent, area of the main plot, were among the main determinants of use and allocation of ONS. Resources positively influenced the proportion of ONS allocated to the main plot in that the more livestock or land area a farmer has, the more organic resources are produced on farm and these will be likely returned to the plots as crop residues or manure. This suggests that positive relationships between the proportion of crop residues applied to main plot and manure used and TLU or area of land in these systems could be a direct influence of an increased amount of ONS that are available in the farms with more livestock and larger areas rather than an ability to get external mineral fertilizer resources. This contrasts with another pattern we might expect, which is that wealthier farmers would be using more agrochemical inputs (i.e., fertilizers) and that reliance on ONS would decrease when one has the ability to buy synthetic inputs. We also noted a pattern with cattle manure where households that relied on the female members of the household for management of ONS applied less cattle manure to their plots compared with those households that were able to hire labor in cash or in kind (more resource endowed farmers). Ability to hire external labor is also a proxy for resource endowment in smallholder farming systems (Grabowski et al 2014).

We noted that farmers who rent or share land allocated a slightly higher proportion of residues back to the main plot compared to those who owned land. One possible explanation for this is that transporting residues from the plots is costly if the rented or shared plot is not near the homestead; alternatively returning residues to the field may be a condition for renting the land. Another reason for this could be that if a renter shows interest to improving soil fertility, they might secure a long-term lease from the owner due to the trust thus gained from the owner (Neef, 2001). Renters retaining greater amounts of residues is contrary to some studies that suggest that farmers who rent or share land do not adopt practices that can improve that land if the resource requirement to do so is high. This is because they consider the need to maximize on the investment that they use in paying rent of land they do not own (Lawin and Tamini , 2019; Fraser 2004, Adjei-Nsiah et al., 2004). Others have shown land tenure not to significantly influence the amount of organic inputs applied in the plots (Leonhardt et al., 2019), suggesting that the relationship between land tenure and residue return to soils is complex and may vary region-to-region in connection with the macro factors discussed above.

### 4.4.4 Socio-cultural Factors in management of ONS (Extension and adherence to norms)

Farmers who interacted with extension workers at least once in the 2018 farming year applied more composted cattle manure to their main plot as compared to those that had no interaction at all. The link between extension visits and manure application is consistent with the important role that extension has been seen to play in influencing on-farm innovation beyond research in both developing and developed communities (Takahashi et al., 2020). In their study of utilization of soil conservation practices, Oyedele et al. (2019) noted that there was a correlation between contact with extension and use of innovations. For farmers to decide to allocate ONS resources (or not) to a plot, they need to be adequately aware of the potential tradeoffs. This awareness can result from interactions with extension, so that the frequency of interactions with extension workers during farm visits or training influences their knowledge about soil fertility management (Ayaji et al., 2007; Pedzisa et al., 2015). If extension workers are not trusted by a population of farmers, the knowledge sharing simply will not work because the social relations are not conducive to having that knowledge “stick”. To put it simply, trust helps makes knowledge (and technology) transfer possible (Carolan, 2006). This underscores the value of including socio-cultural variables into a study such as this.

In contrast to these extension knowledge flows from outside the community, farmers’ awareness of and adherence to social norms are a parallel source of knowledge, potentially influencing a farmer to keep with community ideas of how ONS are managed (Daxini et al., 2018; Liu et al., 2018). In Vihiga, where the norm is to retain fewer crop residues in-field and feed more to livestock, farmers who adhered to social norms retained few residues in their field. Moreover, in all counties, farmers who adhered to social norms of composting (i.e., not composting) applied more uncomposted manure directly to their plots than those who did not. This can be explained in that, as with many other aspects of farming practices, how resources are used also hinges on the awareness a farmer has on how other farmers manage their resources and may follow suit because, as one farmer commented during the focus group discussions “this is what we normally do in this community”. This relatively widespread awareness of norms is consistent with the idea that pressure not to deviate from norms can influence farmers to follow a certain way of managing ONS even though they might think it is not the best way to do so (Lalani et al., 2016). Nevertheless, some non-adherence to norms suggests both the influence of past training and extension efforts as well as innovation potential of farmers and variability that can be a strength when thinking of endogenous innovation and farmers’ ability to adapt. Across all regions, farmers who adhere to social norms of crop residue management tend not to experiment as much with other ONS strategies such as biochar, *Tithonia diversifolia* or composting. These farmers may benefit from training and education on alternative approaches to ONS management and potential benefits.

### 4.4.5 Typologies for ONS management and implications

While ONS allocation and use differed according to farm type, overall ONS produced on all farm types was low as evidenced by the low total maize residues and manures produced due to low livestock ownership. In addition, the actual amounts allocated per unit area may not significantly differ among farm type but the decision to allocate a certain proportion to the field differed was influenced by type. Moreover, if we consider significant losses that may occur during management and grazing (Rufino et al., 2007), these soils are likely to become more nutrient depleted if no supplementary nutrients are added to the farm from exogenous sources. This nutrient depletion will likely lead to continued food insecurity countering efforts to eliminate zero hunger.

Despite resource endowment generally leading to more resources being applied as previously shown, the typology classification indicated that what is driving ONS allocation is not just resource availability, but also other factors such as norms and connections. This is seen in that one would assume that Type 1 farmers who are more resource endowed (as evidenced by the average total inputs produced) linearly applied more animal manure in their fields because they have more livestock that produces manure. However, it is Type 2 (Non-adherent and well connected) farmers that allocate more ONS than other groups. This may be since they are the most trained in areas of soil fertility management and have more interaction with other farmers than Type 1, Type 3 (Adherent and less connected) and Type 4 (Least resource endowed) farmers. They are also well connected with extension agents and have the resources (after Type 1) in terms of organic inputs. They may therefore represent "experimenter farmers" and are likely to adopt and adapt to diverse ways of managing ONS, in accordance also with the fact that not following norms can be considered as indicating the capacity to innovate. This group can be leveraged as "lead farmers" who work with development organizations for farmer-to farmer extension (Franzel et al., 2014; Fisher et al., 2018). Type 4 together with Type 3 farmers allocate more poultry manure to the field than Type 1 and Type 2 farmers - signifying the importance of poultry manure within this group. The need to utilize every resource they have might drive importance placed on poultry manure compared to Type 1 and 2 where other resources that are available in larger quantities tend to be more important.

We note that even within the typologies there is high variability of ONS allocation and overlap between types, as shown in the between class analysis (BCA). Farm types had a limited ability to explain variability and seemed to be structured mainly along the lines of resource endowment; however, the typologies developed provided important insights regarding farmers' access to networks, organizations, and extension. In summary, smallholder systems are complex and share some basic characteristics of ONS allocation to fields. This is important, as targeted training may yield better results for soil fertility management (Chikowo et al., 2014). As such, targeting farm types rather than individual farmers for practices to improve allocation of organic inputs for soil fertility might be a way to cater to the diversity of the farmers in these systems (Rusinamhodzi et al., 2016).

## 4.5 Conclusions

Our findings indicate that beyond resource endowment (livestock, land area, labor), additional factors of location, perceived soil fertility of plot, gender, norms, land ownership, and networks all influence the allocation of ONS to plots. Organizations and extension agents working with farmers on soil fertility management should thus consider these factors and tailor their technologies, trainings, and capacity building efforts in a way that better recognizes the drivers of ONS use. This suggests an ‘options by context’ approach where ONS strategies target different communities based on the preference, norms and farming systems of each community, as opposed to applying a ‘blanket’ approach for all zones. Additionally, since management of legume residues was strongly gendered, engaging with women farmers on options for improved legume residue management is fundamental for developing effective soil fertility management strategies. While typologies were mainly based on resource endowment and offered limited ability to explain variability in resource management, this approach provided important insights about networks, extension, and training within types. Importantly, socio-cultural factors that encourage use of organic inputs such as enhanced connections with farmers through extension, farm groups and peer interaction should be championed if efficient ONS cycling is to happen on farm.

This study advanced our understanding of the factors affecting ONS management in smallholder systems, but future research is needed to explore how this translates in terms of quality of ONS added, nutrient mining, long-term nutrient balances, and the implications for soil health. For example, relating the farm types in different locations and patterns of allocation to actual outcomes of nutrient and soil carbon cycling would be a useful next step in understanding more generally the socio-economic factors that drive sustainability of soil management on smallholder farms globally.

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# Chapter 5: Examining nutrient flows and management options to support soil health in smallholder crop-livestock systems of western Kenya

## 5.1 Introduction

Decline in soil fertility and soil organic carbon (SOC) continue to be a major concern in smallholder farming systems in sub-Saharan Africa (Swanepoel et al. 2016; Vitousek et al., 2009). Nevertheless, these systems are highly heterogenous and so nutrient trends vary considerably across different agroecological contexts and within and between farms. For example, a study by Zingore et al., (2007) in Zimbabwe showed variability in N and P balances based on wealth levels and distance of fields from farmers' homes, such that well-resourced farmers typically had positive balances in all their fields, while medium resourced farmers had positive N and P balances in the fields closest to home and negative balances on outfields furthest from home. The least resourced farmers meanwhile had negative N and P balances in all their fields. In another study, Jiri and Mafongoya (2018) showed that agroecological zone and cropping system had an overall influence on N and P balances, although there was general trend of negative N balances and more neutral P balances.

Due to this high level of spatial and socio-economic variation in nutrient flows and SOC dynamics (Vågen et al., 2005), context specific nutrient management is key to supporting soil health (and multiple ecosystem services) and increasing or sustaining crop yields. In order to foster improved soil management, nutrient budgeting and modeling approaches can play a key role by accounting for the various flows of nutrients and C into and out of agroecosystems, indicating both overall levels of sustainability across different farms and also identifying the management levers available to reverse long-term declines.

In our study region of western Kenya, there are highly leached tropical soils that are often highly acidic, have low base saturation and high P fixation capacity (Sanchez et al.,2019), so that it becomes even more important to assess nutrient inputs and losses to maximize nutrient use efficiency. Often the most limiting nutrient for crop growth, N is of particular concern yet the maize-based systems in Kenya have reported net losses of 42 kg N ha$^{-1}$ yr$^{-1}$ or more (Stoorvogel, et al., 1993; Vitousek et al. 2009). This highlights the need to decrease non-productive losses (leaching, erosion, denitrification) and replenish N lost through harvest via organic nutrient inputs and/or fertilizer applications. At the same time, P depletion may be around 1 kg P ha$^{-1}$ yr$^{-1}$ in this region (Stoorvogel, et al., 1993), which is less extreme than that for N but indicates that small changes in P flows may not be enough to overcome historical fertility depletion in these systems and the tendency for P fixation by oxide clays in high-rainfall areas (Margenot et al., 2017).

In spite of the overall negative balances estimated for sub-saharan Africa (Kabirigi et al., 2016; van Beek et al., 2016), it is not clear how these balances have changed in recent years in light of innovations such as conservation agriculture, integrated soil fertility management and agroforestry throughout the region (Kihara et al., 2020). Previous research in our study area on a range of farms showed that there is wide zone-to zone variation in the management of soil nutrient inputs associated with different farm typologies (Nyamasoka-Magonziwa et al., 2021). In western Kenya, communities differ in terms of land holding, farming systems and organization with clear implications for organic matter inputs and cycling (Van de Steeg, et al., 2010; Nyamasoka-Magonziwa et al., 2021). While previous studies have examined nutrient flows and residue management in the region, most have focused on partial budgets encompassing only fertility inputs and harvest and have not considered losses such as erosion and leaching, which are known to affect nutrient balances.

In addition, these analyses have not extended to assessing SOC trajectories in smallholder systems. As a key element of soil health, soil organic matter is important for various soil functions such as regulating biogeochemical cycling of nutrients, improving soil physical properties such as aeration, water retention and aggregate stability (Bationo et al., 2007; Johnston et al., 2009). These benefits of SOC are critical for increasing crop productivity and resilience especially in low-input systems. In many regions SOC has decreased considerably due to changes in land use, tillage and lack of organic matter inputs (de Blécourt et al., 2019). Understanding future trajectories of C stocks under current practices and what efforts can be done to slow down SOC decline is critical to reversing this trend. Possible ways to restore SOC stocks in smallholder farming communities include crop residue retention, soil erosion control, reduced tillage, and addition of organic inputs such as high biomass cover crops, manure, compost and biochar (Lal, 2004; Corbeels et al., 2019). Model predictions of SOC trends have been limited for use in smallholder systems due to a lack of data for model calibration that is relevant to smallholder contexts (Nyawira et al., 2021).

The general objective of this study was therefore to estimate N, P and K balances and SOC trends in representative smallholder farming plots and the implications for soil health across different agroecological zones in western Kenya and explore options to restore SOC and overall soil fertility in smallholder systems. Specifically, we sought to: i) evaluate the current N, P, K and C flows and balances within a representative range of farms in western Kenya (i.e., representative of different farm types within a previously developed typology); ii) determine the main drivers of nutrient balances and C stocks on these farms and iii) to predict how management interventions could influence future N, P and K balances and C stocks based on multiple scenarios compared to a business-as-usual scenario drawn from the current managemnet of these farms.

In a previous survey conducted within the same area (Nyamasoka-Magonziwa et al., 2021), we identified four farm types embodying different levels of farm resource endowment, social connectedness, and residue management. Type 1 farmers were generally more resource-endowed with more livestock and larger pieces of land; Type 2 farmers are non-adherent to social norms pertaining to management of organic nutrient sources and are well connected to extension and other farmers. Type 3 and 4 farmers (collapsed in this paper as Type 3 based on relatively subtle differences between them) are the least resource endowed, generally adherent to social norms of soil fertility management, and are less connected to extension and other farmers compared to Type 1 and Type 2 farmers. We hypothesized that this least resource endowed (Type 3) farms would have more negative N, P, and K balances in all their plots (see Fig. 5.1 for a graphical representation of these hypotheses regarding farm types and field locations). At the same time, we anticipated that Type 2 farmers would have positive balances in the main plots and negative nutrient balances in the secondary plots, while Type 1 farmers would have positive nutrient balances in both the main plots and secondary plots productive plot as illustrated in Fig. 5.1. We also hypothesized that nutrient balances and C are influenced by agroecological zone location, farm type, and environmental factors, such as those influencing erosion rates and other key nutrient losses from systems.

With regards to future nutrient management scenarios, we anticipate that retaining all residues, controlling erosion and complete residue removal for feed (with return of the manure produced) would significantly affect N, P, and K balances and SOC trends over time.

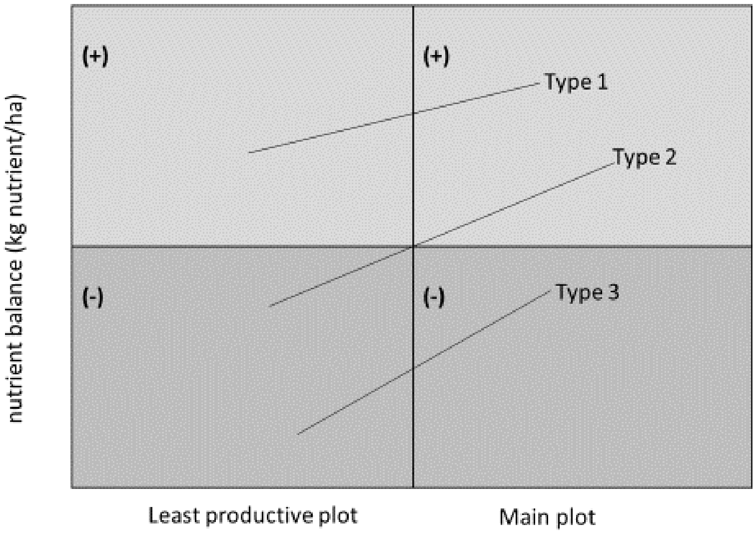

**Figure 5.1**: Hypothesized nutrient balance trends by farm type and plot category in smallholder farms.

To test these hypotheses, we analyzed nutrient balances and modeled the SOC stocks on 18 farms across three agroecological zones and three farm types, using management information drawn from case study surveys regarding 2 fields from each farm. We also modeled changes in management using different scenarios, to guide the possible courses of action to improve nutrient balances and SOC stocks.

## 5.2 Materials and Methods

The study was carried out in western Kenya in three districts: Nandi (with a humid subtropical and tropical rainforest climate), Busia (with a tropical savanna climate) and Vihiga (with a tropical rainforest climate), located in different agroecological zones as described in (Nyamasoka-Magonziwa 2021). Following a survey carried out in 2019, eighteen farming households were selected for a detailed study of nutrient balances (i.e., 2 farms from three most represented farm typologies in each community making 6 case studies per zone).

### 5.2.1 Determining nutrient inputs and crop exports

A detailed case study of nutrient flows into and out of the main (most productive) plot and secondary (least productive) plot for each was carried out (in practice these were most commonly the only two fields owned by the farmer). The farmer, guided by an enumerator in a participatory mapping approach, made physical drawings to map the position of each plot relative to the home, and then the flows of organic amendments and fertilizer additions to and from the plots were estimated based on data for both the long and short rainy seasons in 2018 (see Figure 5.2).

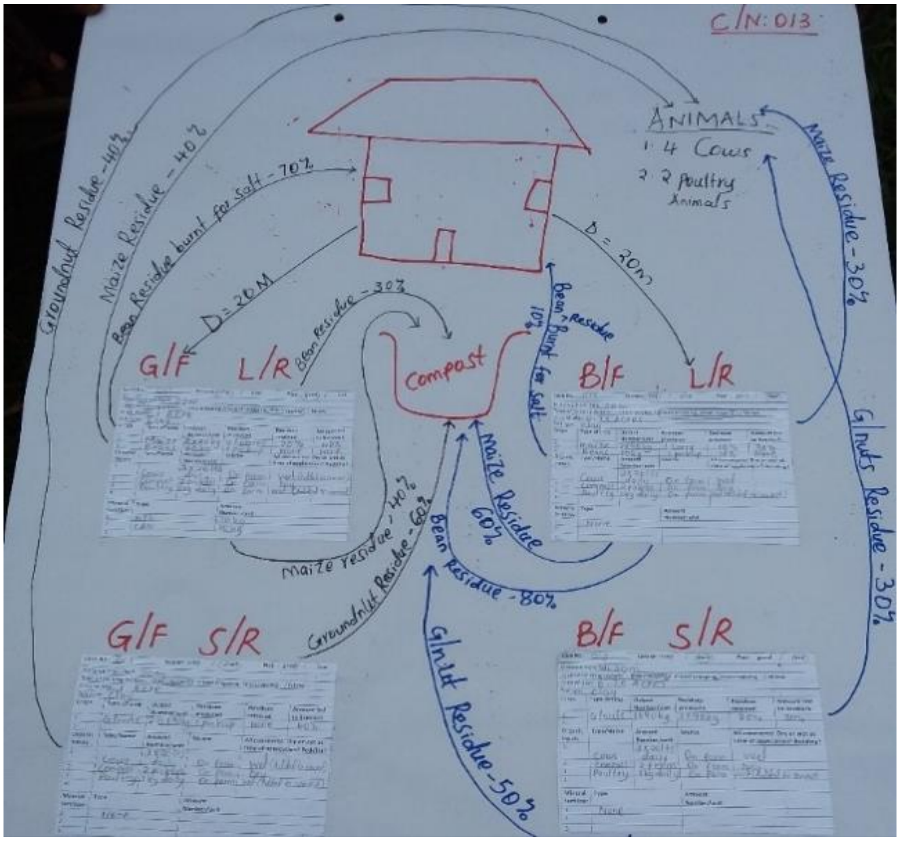

**Figure 5.2**: An example of a resource flow diagram to and from the main plot and secondary plots for two growing seasons in a typical year, as drawn by a farmer and assisted by an enumerator in western Kenya. The diagram is organized to show flows from main field (G/F) or secondary field (B/F) for the long rainy season (L/R) and short rainy seasons (S/R). It shows other components of farmstead, distance from home and the percent of residues transferred with each flow.

Manure, compost, farmyard manure and biochar samples were collected from households by bulking together several samples from each source (pile, animal yard, etc.) and were analyzed for total C, N, P and K using standard procedures (Table 5.1). Kitchen waste composition was estimated in consultation with farmers and technicians and considered to be made up of a variety of organic components such as potato peels, banana peels, wood ash, vegetable cutoffs, eggshells, corn cobs and peels. We then calculated the weighted contribution of each organic input to see the N/P/K composition of a typical kitchen waste as highlighted by key informants. The actual amount of N, P, and K applied to each plot from the organic amendments and mineral fertilizers, respectively was calculated by multiplying the total dry biomass and fertilizer (kg ha$^{-1}$) inputs by the % nutrient content of the organic biomass or fertilizer (reported in Table 5.1).

Nutrient composition of the stover biomass and grain biomass of the common crops grown in the cases studies were estimated from literature (Table 5.2). These values were then used to calculate the N, P, and K exported from the fields (kg ha$^{-1}$) by multiplying the total dry matter grain yield kg ha$^{-1}$ and stover yield kg ha$^{-1}$, assuming a harvest index of 0.4. To estimate N inputs from biological nitrogen fixation, we used data on N fixation rates by common bean (*Phaseolus vulgaris*), soybean (*Glycine max*), groundnut (*Arachis hypogaea*) in western Kenya reported by Ojiem et al. (2007) and assumed bambara nuts *(Vigna subterranean)* to be similar to groundnut. Estimated percentage of N fixed by each legume crop was multiplied by the total N in grain and residues, along with root inputs and N contents, based on root to shoot ratios from the literature.

**Table 5.1:** Nitrogen, Phosphorus and Potassium concentrations of sampled organic inputs from smallholder farms and mineral fertilizers used in western Kenya

| | | N | P | K |
|---|---|---|---|---|
| | | --------------- | % | --------------- |
| Organic inputs | Biochar (from sugarcane bagasse) | 0.56 | 0.03 | 0.73 |
| | Goat manure | 2.38 | 0.60 | 1.23 |
| | Cattle manure | 1.45 | 0.44 | 0.67 |
| | Poultry manure | 2.46 | 0.64 | 1.47 |
| | Farmyard manure | 1.81 | 0.39 | 0.90 |
| | Compost | 1.86 | 0.37 | 1.90 |
| | Kitchen waste* | 0.24 | 0.57 | 1.88 |
| Inorganic inputs | DAP 18-46 | 18.0 | 20.0 | - |
| | Mavuno brand fertilizer | 10.0 | 11.0 | 10.0 |
| | Urea | 46.0 | - | - |
| | Triple Superphosphate | - | 19.5 | - |
| | Calcium Ammonium Nitrate | 27.00 | - | - |
| | Sympal (specialized fertilizer for legumes) | - | 23.0 | 16.0 |

*Kitchen waste composition was estimated in consultation with farmers and technicians and considered to be made up of a variety of organic components such as potato peels, banana peels, wood ash, vegetable cutoffs, eggshells, corn cobs and peels. We then calculated the weighted contribution of each organic input to see the N/P/K composition of a typical kitchen waste as highlighted by key informants.

**Table 5.2:** Nitrogen, Phosphorus and Potassium values for the commonly exported crop grain and residues from the crops grown by the selected case study farmers in three regions in western Kenya [data collected from Okalebo et al., 2002; Salvagiotti et al., 2008; Musa and Singh, 2019]

| | **Crop** | **N** | **P** | **K** |
|---|---|---|---|---|
| | | ----------------*% content*------------------ | | |
| **Grasses** | Maize stover/residues *(Zea mays L)* | 0.89 | 0.08 | 2.79 |
| | Maize grain | 0.89 | 0.20 | 0.44 |
| | Napier grass *(Pennisetum purpureum*) | 1.02 | 0.11 | 2.63 |
| **Legumes** | Common beans residues *(Phaseolus vulgaris)* | 1.20 | 0.13 | 2.09 |
| | Common beans grain | 2.50 | 0.36 | 1.30 |
| | Soyabean grain *(Glycine max)* | 6.34 | 0.24 | 1.90 |
| | Soyabean residue | 1.21 | 0.36 | 1.30 |
| | Ground nuts grain (*Arachis hypogaea)* | 4.60 | 0.40 | 0.70 |
| | Ground nut residue | 1.50 | 0.24 | 1.90 |
| | Bambara nuts grain (*Vigna subterranean)* | 3.25 | 0.40 | 0.70 |
| | Bambara nuts residues | 2.79 | 0.24 | 1.90 |
| | Lablab *(Lablab purpureus*)* | 1.31 | 0.33 | -- |
| **Tubers** | Sweet potatoes *(Ipomoea batatas)* | 0.24 | 0.04 | 0.50 |
| | Cassava tuber *(Manihot esculenta)* | 0.22 | 0.03 | 0.22 |
| | Cassava residues | 1.10 | 0.12 | 0.50 |
| **Others** | Leafy vegetables (*Brassica species)* | 0.50 | 0.06 | 0.44 |

* no data on K concentration was available for lablab, so this was assumed the same as soybean residue

## 5.2.2 Calculating N, P and K balances

Net N, P and K balances for the combined long and short rainy seasons were calculated using a similar approach to Vanek and Drinkwater (2013) using equations 5.1, 5.2 and 5.3 below respectively.

$$N_{balance} = (IN_{N1} + IN_{N2} + IN_{N3}) - (OUT_{N1} + OUT_{N2} + OUT_{N3} + OUT_{N4} + OUT_{N5}) \qquad (5.1)$$

$$P_{balance} = (IN_{P1} + IN_{P2}) - (OUT_{P1} + OUT_{P2} + OUT_{P4}) \qquad (5.2)$$

$$K_{balance} = (IN_{K1} + IN_{K2}) - (OUT_{k1} + OUT_{k2} + OUT_{k3} + OUT_{k4}) \qquad (5.3)$$

where for each nutrient input are IN and outputs are OUT. $IN_1$ refers to inputs from mineral fertilizer, and $IN_2$ represents nutrient flows of organic inputs. $IN_3$ represents inputs from biological N fixation. $OUT_1$ corresponds to grain exports and $OUT_2$ reflects nutrient in removed aboveground residues. $OUT_3$ represents leaching for N and K estimated using methods by (Lesschen et al., 2007), while $OUT_4$ reflects losses of N, P, and K due to erosion (see below). $OUT_5$ refers to gaseous losses of N). Additional details are provided in Table 5.3.

Soil loss due to erosion was calculated using the revised universal soil loss equation (RUSLE) according to the following formula.

$$A\ (Mg\ ha^{-1}\ yr^{-1}) = R*K*(LS)*C*P \qquad (5.4)$$

See Table 5.4 for definitions of each term in the equation. Nutrient losses were calculated by multiplying the estimate nutrient content of the 0-30 cm layer of soil by the amount of soil lost. All the soil parameters required (for leaching, gaseous losses and erosion) were extracted from Soil Grids (https://soilgrids.org) where layered soil data (0-5 cm, 5-15 cm and 15-30 cm) was weighted to get the average soil parameters for the 0 to 30 cm depth.

**Table 5.3**: Equations used to estimate nutrient losses and inputs from soils through leaching and gases (NutMoN model) and erosion (using the Revised Universal Soil Loss Equation - RUSLE model) from soils across three locations (Nandi, Vihiga and Busia) in western Kenya

| | **Equation** | **Source** |
|---|---|---|
| $IN_{N1}$,<br>$IN_{K1}$,<br>$IN_{P1}$ | N/P/K input from mineral fertilizers (kg $ha^{-1}$ $yr^{-1}$) | Vanek and Drinkwater (2013), Smaling et al., (1993) |
| $IN_{N2}$ , $IN_{P2}$, $IN_{K2}$ | N/P/K input from exogenous organic inputs (kg $ha^{-1}$ $yr^{-1}$) | |
| $IN_{N3}$ | $N_{BNF} = \% N * (N_{grain} + N_{residue} + N_{roots})$<br>Where $N_{BNF =}$ N (kg $ha^{-1}$ $yr^{-1}$) input from biological nitrogen fixation (BNF), % N is the % N fixed by the legume estimated from Ojiem et al.(2007), $N_{grain}$ and $N_{residue}$ is total N in residues and grain respectively and $N_{roots}$ is total N in roots based on root to shoot ratio from literature values. | |
| $OUT_{N1}$, $OUT_{P1}$, $OUT_{K1}$ | N/P/K in exported stover (kg $ha^{-1}$ $yr^{-1}$) = Stover harvested - stover retained* % N/P/K in stover<br>Where stover harvested is estimated from (0.4 harvest index) of farmer reported grain yield | |
| $OUT_{N2}$,$OUT_{P2}$, $OUT_{K2}$ | N/P/K in exported grain (kg N $ha^{-1}$ $yr^{-1}$) = Grain yield kg ha-1 $yr^{-1}$) * % N in stover | |
| $OUT_{N3}$ | *Based on the transfer functions regression models developed by Lesschen et al., 2007*<br>$N_{leaching}$ (kg N·$ha^{-1}$ $yr^{-1}$) = (0.0463 + 0.0037 *(Prec./(Cl x Z)))*(Nin+ 0.014*SON - Nuptake)<br>Where Prec = annual precipitation (mm); Nin = Total N inputs from the balances data sheets (kg $ha^{-1}$); SON (Soil organic nitrogen) = Nin *0.98 (as about 98% of Total N is organic); Cl = clay content (%) from Soil Grids - https://soilgrids.org; Z = rooting zone in meters (used 1.2m for maize); N uptake = N in all exports +roots (kg/ha) and 0.014 is decomposition rate | Lesschen et al., (2007) |
| $OUT_{K3}$ | *Based on the transfer functions regression models developed by Lesschen et al., 2007*<br>$K_{leaching}$ (kg K $ha^{-1}yr^{-1}$) = -6.87+0.0117*Prec. +0.173*$K_{in}$ – 0.265*CEC<br>Where Prec=annual precipitation in mm, Kin=Total K inputs fro the balances data sheets, CEC=cation excahnge capacity (cMol/kg) from soil grids-https://soilgrids.org/ | |
| $OUT_{N4}$,<br>$OUT_{P4}$,$OUT_{K4}$ | N/P/$K_{erosion}$ (kg $ha^{-1}yr^{-1}$) = A kg $ha^{-1}$ $yr^{-1}$ * % N/P/K<br>Where A is the rate of erosion (see RUSLE Model in Table 4 and %N and P is the soil total N concentration and % K is exchangeable K in soil | |
| $OUT_{N5}$ | *Based on the transfer functions regression models developed by Lesschen et al., 2007*<br>$N_{gaseous}$ (kg N·$ha^{-1}yr^{-1}$) = 0.025+ 0.000855*Prec.+0.13*$N_{in}$ + 0.117*SOC<br>Where Prec = annual precipitation in mm; Nin = Total N inputs from the balances data sheets; SOC=soil organic carbon % (from Soil Grids- https://soilgrids.org) | Lesschen et al., (2007) |

**Table 5.4:** Parameters for the revised universal soil loss equation (RUSLE) model used to calculate erosion from smallholder plots in western Kenya.

| | **Parameter** | **Source(s)** |
|---|---|---|
| R | Rainfall erosivity in MJ mm ha$^{-1}$ h$^{-1}$ yr$^{-1}$ | Panagos et al., (2017) |
| K | $K = [2.1*10^{-4}*M^{1.14}*(12-OM) +3.5*(s-2) +2.5*(p-3)]/759$<br>Where K is the soil erodibility, M is (%silt*100-%clay), OM = % organic matter, s = soil structure where 2 is for moderate or coarse granular, p = permeability where 3 is for slow to moderate | Wischmier and Smith (1978);<br>Ghosal and das Battachrya, (2020) |
| L | L = (λ / 22.13) ^ m<br>λ is the slope length in m; m =0.3 if slope % is between 1 and 3, m = 0.4 if slope % is between 3 and 5, m = 0.5 if slope % is between 5 and 12, m = 0.6 if slope % is 12 or more | Wischmier and Smith (1978) |
| S | S = (S / 9) ^1.35<br>where S is slope angle in % | Schmidt et al. (2019) |
| C | C = 0.34 | Gabriels et al. (2003)<br>Ghosal and das Battachrya, (2020);<br>Angima et al. (2003) |
| P | P = 1 | Angima et al. (2003),<br>Ghosal and das Battachrya (2020) |

### 5.2.3 Management Scenarios for Nutrient Balance and Soil Carbon Modeling

Scenarios were compared to current farmer practice, or business as usual (BAU), for each case study for N, P, K balances Table 5.5). The scenarios were:

i) Reduced erosion, where slope length was interrupted by contour features such as live barriers or stone walls to slow and/or catch runoff, thus dividing slope length by 3; a new LS (slope factor) was then calculated to compute an alternative rate of erosion, and then this new rate was factored into equation 5.1 above.

ii) Complete residue removal-shift to manure, where all residues were considered to be removed from the field and fed to cattle. We then assumed that 45% of the biomass in the residues was returned to the field as manure.

$$Cattle\ Manure_{(N/P/K)} = (TR*0.45)*(\%\ N/P/K)/100 \qquad (5.5)$$

where TR = Total residue biomass produced in kg ha$^{-1}$ yr$^{-1}$, 0.45 is the conversion efficiency of crop residues (dry matter intake) to manure (dry matter output) as described by Nennich et al., (2005); % N/P/K refers to the content of each nutrient in cattle manure as reported in Table 5.1.

iii) 100% residue retention (i.e., no crop residue exports), while retaining the current rate of manure input. This assumes manure comes from sources other than crop residue taken from the field of interest.

Meanwhile, for SOC stocks, the three scenarios above were implemented, as well as two additional scenarios that were considered to have especially large impacts on SOC dynamics (Table 5.5):

iv) Change from a maize-common bean rotation to maize-lablab (*Lablab purpureus*, a high biomass legume) rotation

v) Best case scenario with reduced erosion, residue retention and a maize lablab rotation

**Table 5.5:** Description of the scenarios for modeling soil organic carbon stocks and nutrient balances in western Kenya. The alternative scenarios below are based on business-as-usual inputs, but with modification to one or more of the input and/or export flows.

| **Scenario** | **Model inputs** | **Nandi** | **Busia** | **Vihiga** |
|---|---|---|---|---|
| Business as usual (BAU) | crop | Maize-bean | Maize-bean | Maize-bean |
| | Manure/ compost Mg ha$^{-1}$ yr-1 | 1.517 | 0.604 | 0.407 |
| | Fertilizer kg /ha /yr. | 245 | 137 | 274 |
| | Residues % removal | 75 % | 40 % | 75 % |
| | Erosion rate Mg ha$^{-1}$ yr$^{-1}$ (median) | 25.2 | 39.2 | 42.3 |
| | Tillage/weed control | Hand hoeing | Hand hoeing | Hand hoeing |
| Reduced erosion | Erosion rate Mg ha$^{-1}$ yr$^{-1}$ (median) | 16.9 | 24.6 | 27.0 |
| Residue retention | Residues % removal (on both maize and beans) | 0 % | 0 % | 0 % |
| Complete residue removal-shift to manure | Manure/compost (Mg ha$^{-1}$ yr$^{-1}$) | 2.023 | 1.51 | 0.542 |
| | Residues % removal | 100 % | 100 % | 100 % |
| High biomass legume | crop | Maize-lablab | Maize-lablab | Maize-lablab |
| Best case | crop | Maize-lab lab | Maize-lab lab | Maize-lab lab |
| | Erosion- reduced | 16.85 | 24.6 | 27.0 |
| | Residues % removed | 0 % | 0 % | 0 % |

### 5.2.4 Carbon Modelling

Carbon stocks (i.e., total C, active, slow, and passive pools) were simulated using the DayCent model (version DD17centEVI; Del Grosso et al., 2001). First, a spin-up was run for 4000 years to simulate an evergreen tropical forest typical of original vegetation in the western Kenyan highlands with tree removal by natural fire events every 10 years, simulating pre-settlement land use history of the region. Next, a base cropping was run for 50 years, and it included a maize-bean rotation (maize in the long season and bean in the short season) with no additional inputs. Thereafter, business as usual and alternative management scenarios for three agroecological zones

(Table 5.5) were simulated. Rough validation of the model was done by comparing biomass and yield simulated in the model with actual yield obtained in the region (actual average maize grain yield: 2.6 Mg ha$^{-1}$ (Nymamsoka_Magonziwa et al., 2020) vs. modeled maize grain yield range: 1.125 to 3.75 Mg ha$^{-1}$ at around 50 years from base cropping), as well as SOC under model equilibrium (4.4 %) and native forest soil (4.2%, as reported in Chapter 3).

As for the nutrient balances described above, soil input variables (i.e., sand, silt and clay content) were taken from the soilgrids.org soil mapping database (https://soilgrids.org/). Daily weather variables (i.e., total precipitation, mean max temperature and mean min temperature were estimated using the NASA-Power remotely sensed database for historical weather data, (https://power.larc.nasa.gov/) and repeated for 25-year intervals to build up the required time period for each model run. Management variables, such as manure inputs, fertilizer inputs, proportions of residues removed, and crop calendar events were taken from the average from each region reported in the case studies and triangulated with key informants. Estimated C:N ratios and lignin contents of organic inputs were taken from regional literature values. Default crop parameters for maize and common beans were used and hairy vetch crop parameters were adjusted to suit a high biomass tropical legume like lablab, using data from Ojiem et al. (2007).

### 5.2.5 Statistical analysis

All analyses were done in R version 3.6.2 (R Core team, 2019). Differences in the mean nutrient inputs, outputs and balances between locations and farm types were analyzed using two-way ANOVA with the lsmeans package (Lenth, 2016) and differences in means analyzed with Tukey honestly significant difference (with $p < 0.05$). The overall balances and flows between the main plot and secondary plots were compared using t-tests. Simple linear regression was used to assess bi-variate correlations between overall nutrient balances and erosion rates. Data for regressions and ANOVA were checked for fit to model assumptions.

## 5.3 Results

### 5.3.1 Overall nutrient balances

Net N, P and K balances were highly variable across the 18 case studies (35 fields). Overall N balances ranged from -189.2 to 37.8 kg N $ha^{-1}$ $yr^{-1}$ (average -73.9 kg N $ha^{-1}$ $yr^{-1}$), while P balances ranged from -54.2 to 94.6 kg P $ha^{-1}$ $yr^{-1}$ (average of 3.0 kg P $ha^{-1}$ $yr^{-1}$) and K balances ranged from -203.6 to 30.9 kg K $ha^{-1}$ $yr^{-1}$ (average of -39.7 kg K $ha^{-1}$ $yr^{-1}$).

### 5.3.2 Nutrient balances by location, farm type and field type

While there were no significant differences in overall N, P or K balances between locations, the Vihiga zone had the least negative mean N balance (-65.4 kg N $ha^{-1}$ $yr^{-1}$); with Busia and Nandi having balances of -77.9 and -77.7 kg N $ha^{-1}$ $yr^{-1}$; respectively (Fig. 5.3). Phosphorus balances were slightly negative in Busia (-2.7 kg P $ha^{-1}$ $yr^{-1}$) and Vihiga (-3.01 kg N $ha^{-1}$ $yr^{-1}$) and were positive in Nandi (14.2 kg P $ha^{-1}$ $yr^{-1}$). Potassium on the other hand was negative across the three locations (average across locations: -39.9 kg K $ha^{-1}$ $yr^{-1}$).

Nitrogen balances were not significantly different across the three farm types (Fig. 5.4), but Farm Type 2 had, on average, slightly more negative N balances (Type 2: -74.6 kg N $ha^{-1}$ $yr^{-1}$; Type 1: -65.0 kg N $ha^{-1}$ $yr^{-1}$; Type 3: -67.9 kg N $ha^{-1}$ $yr^{-1}$). Phosphorus balances on the other hand were positive on average for Type 1 (2.02 kg P $ha^{-1}$ $yr^{-1}$) and Type 2 farmers (4.9 kg P $ha^{-1}$ $yr^{-1}$), but were slightly negative for Type 3 farmers (-1.3 kg P $ha^{-1}$ $yr^{-1}$). Potassium balances were negative across the farm types (average across types: -37.1 kg K $ha^{-1}$ $yr^{-1}$).

There were no differences noticed for nutrient balances between main plots and least productive (secondary) plots (-72.4 vs. -74.4 kg N ha$^{-1}$ yr$^{-1}$; 3.9 vs. 2.6 and kg P ha$^{-1}$ yr$^{-1}$ and -40.4 vs. -39.1 K ha$^{-1}$ yr$^{-1}$; for main vs. least productive plots, respectively). All farm types had negative N and K balances in both their field types except for Type 2 farmers and Type 3 farmers that had slightly positive P balances in their main fields and least productive plots respectively.

### 5.3.3 Main drivers of nutrient balances

To understand the main drivers of nutrient balances we examined the relative magnitude of the various inputs and outputs across different farm types and agricultural zones. In general, the biggest drivers of nutrient balances were mineral fertilizer inputs and outputs via erosion and harvest. Mineral fertilizer use was an important input, contributing 61.9 %, 64.9 %, and 12.7 % of total N, P and K inputs, respectively. Mineral fertilizer N input was significantly higher in Vihiga than Busia and Nandi when averaged across farm types ($p=0.01$; average mineral N input across zones: 40.0 kg N ha$^{-1}$ yr$^{-1}$), but P input did not significantly differ across locations (average mineral p input across zones: 25.5 kg P ha$^{-1}$ yr$^{-1}$) and K (average mineral K input across zones: 5.5 kg N ha$^{-1}$ yr$^{-1}$; Fig. 5.3). Mineral fertilizer input did not differ significantly among farm types (Fig. 5.4).

Total manure and compost application was low (averaging 855 kg ha$^{-1}$ year$^{-1}$) across the three zones and represented 38.1 % and 35.1 % of total N and P inputs, respectively. Manure/compost applications rates differed significantly across the three locations ($p=0.03$), being highest in Nandi (1517 kg ha$^{-1}$ yr$^{-1}$) and lowest in Vihiga (403 kg ha$^{-1}$ yr$^{-1}$). However, organic inputs did contribute substantially to K inputs (87.1% of total; Figure 5.3C). Overall manure application rates differed significantly among farm types with Type 2 applying nearly twice as much as Type 1 and over 6 times as much as Type 3 farmers; (Type 2:1 541 kg $ha^{-1}$ $yr^{-1}$ vs Type 1- 736 kg $ha^{-1}$ $yr^{-1}$ vs Type 3-279 kg $ha^{-1}$ $yr^{-1}$; p=0.02) .

Nutrient loss by erosion was the most important driver of N and P losses, but less so for K losses across the three regions. The average nutrient losses from erosion across the three regions were 50.6 kg N $ha^{-1}$ $yr^{-1}$, 14.1 kg P $ha^{-1}$ $yr^{-1}$ and 1.9 kg K $ha^{-1}$ $yr^{-1}$. Vihiga had higher erosion losses of N and P nutrients (Fig 5.3a, 5.3b) in line with its higher rate of erosion relative to the other two regions (Erosion rate Vihiga: 52.7 Mg $ha^{-1}$ $yr^{-1}$ ; Busia: 42.1 Mg $ha^{-1}$ $yr^{-1}$and Nandi: 29.2 Mg $ha^{-1}$ $yr^{-1}$). The erosion rate was highly negatively correlated to N balances (p=0.001; $r^2$=0.68; Fig 5.5) and with P balances (p=0.001; $r^2$=0.31; Fig 5.5), but did not influence K balances across the three regions.

Crop and residue harvest was the most important driver of K exports and were highest in Nandi resulting in more negative K balances than in Busia and Vihiga (Fig. 5.3C). Similarly, N losses from crop exports were higher in Nandi than the other two regions as well. When looking at the different farmer types, Type 2 farmers exported the most K through crop harvest (Fig 5.4C).

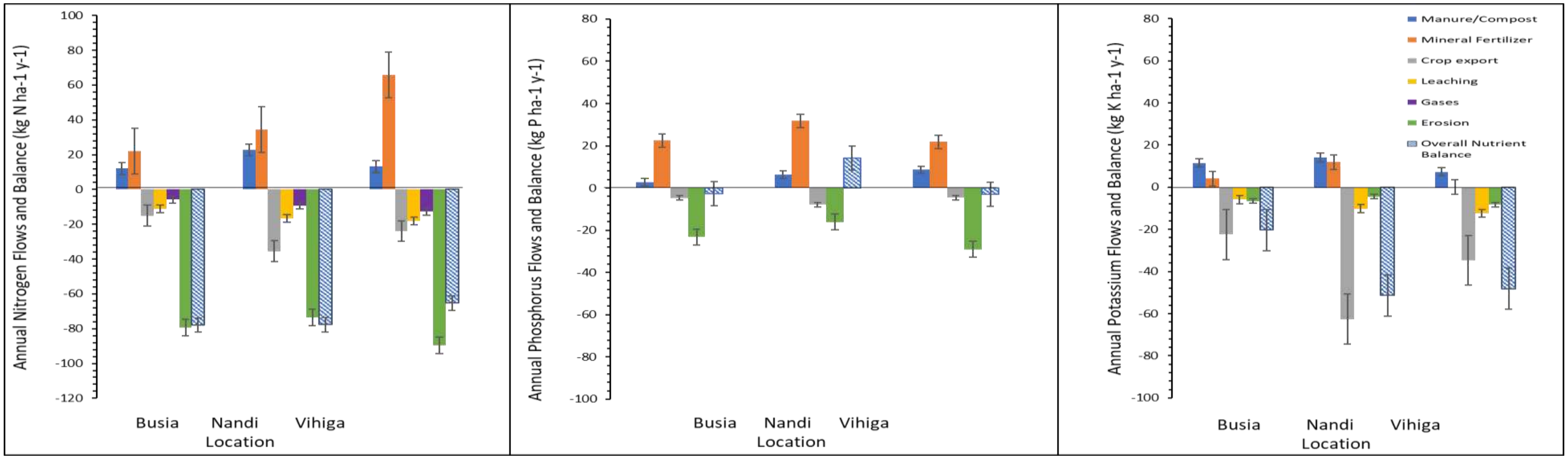

**Figure 5.3**: Nutrient inputs, outputs, and net balances across all 35 fields for a) nitrogen b) phosphorus and c) potassium across three agroecological location (communities) in western Kenya; Busia (n=12); Nandi (n=12); Vihiga (n-11).

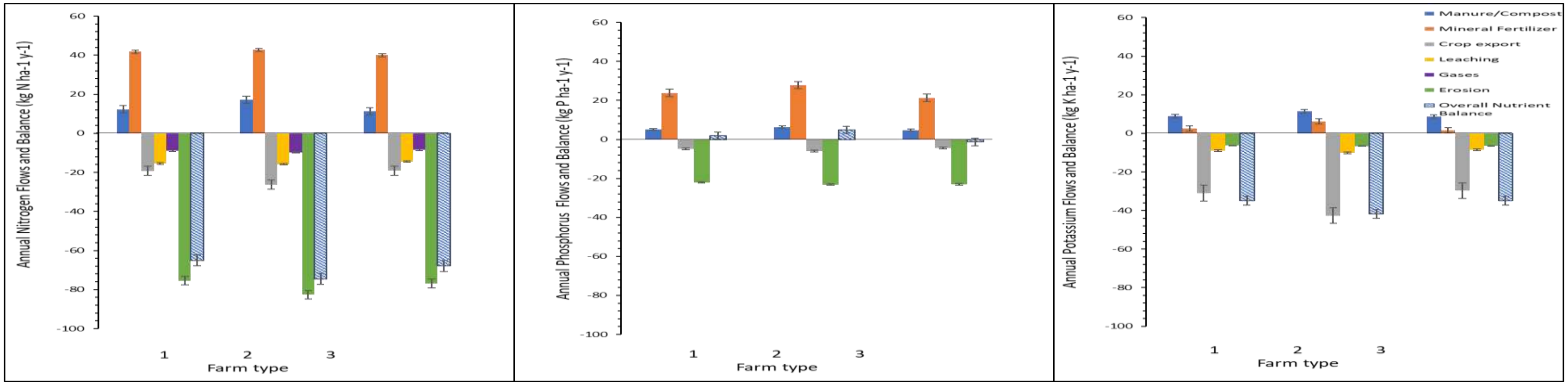

**Figure 5.4**: Nutrient inputs, outputs, and net balances across all 35 fields for a) nitrogen b) phosphorus and c) potassium as influenced by farm type in western Kenya; Type 1 (n=11); Type 2 (n=12); Type 3 (n=11).

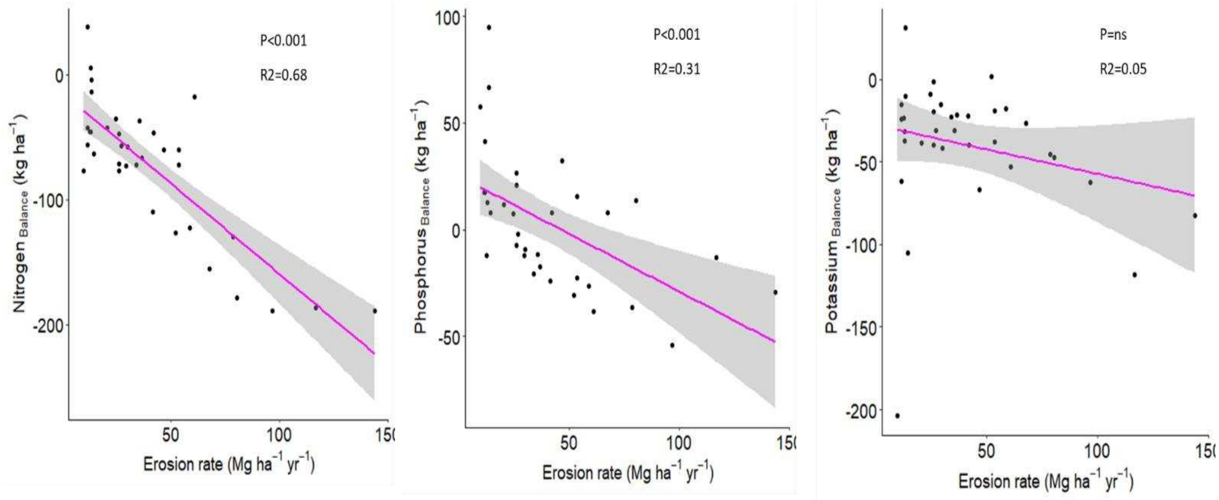

**Figure 5.5:** Nutrient Inputs, outputs, and total balances for a)nitrogen b) phosphorus and c) potassium as influenced by farm type location in w. Kenya.

### 5.3.4 Effects of management scenarios on NPK balances

When examining different modeled scenarios to understand the effect of improved soil nutrient management on nutrient balances, the reduced erosion scenario (by reducing the slope length) had the greatest impact on nutrient balances for all nutrients in all locations. The reduced erosion scenario cut N losses by half, nearly doubled the net gain of P and reduced K losses by approximately 5 kg K ha$^{-1}$ yr$^{-1}$ across zones compared to BAU. (Table 5.6). Residue retention scenario had the highest impact on K balances, reducing K depletion by an average of 29.5 kg ha$^{-1}$ yr$^{-1}$ across the three locations vs. 10.6 kg ha$^{-1}$ yr$^{-1}$ for N balances and 1.3 kg ha$^{-1}$ yr$^{-1}$ for P balances, relative to BAU (Table 5.6). Removing all residues and returning 45% of them as manure resulted in minimal influences on overall nutrient balances across the three locations.

### 5.3.5 Effects of management scenarios on soil organic carbon

After 50 years from base cropping, the scenario of complete residue removal-shift to manure had the lowest total SOC (14.2 Mg C ha-1) followed by BAU (15.5 Mg C ha-1). The residue retention, reduced erosion and high biomass legume scenarios had higher SOC stocks (17.6 Mg C ha$^{-1}$, 20.6 and 20.0 Mg C ha$^{-1}$, respectively; Figure 5.6) in Busia, with simiar trends in Nandi and Vihiga. Soil organic carbon stocks were lowest in Vihiga compared to other locations. The best case scenario had nearly double the C Stocks as the BAU scenario 50 years after base cropping across all locations (Busia: 28.4 Mg C ha$^{-1}$; Nandi: 34.55 Mg C ha$^{-1}$ and Vihiga: 27.9 Mg C ha$^{-1}$). This scenario had a more gradual decline in C stocks over the 150 years post base cropping comapred to the other scenarios.

**Table 5.6**: N, P, and K balances for business as usual (BAU) compared to three scenarios of: Complete residue removal-shift to manure, reduced erosion and 100% residue retention in 3 agroecological zones in w. Kenya. Numbers in parentheses are standard error of means (se).

| Scenario | Busia (n=12) | | | Nandi (n=12) | | | Vihiga (n=11) | | |
|---|---|---|---|---|---|---|---|---|---|
| | N | P | K | N | P | K | N | P | K |
| | | | | | *kg* $ha^{-1}$ $yr^{-1}$ | | | | |
| BAU | -77.9 (17.1) | -2.7 (12.6) | -20.4 (6.60) | -77.7 (12.7) | 14.2 (4.91) | -51.4 (15.9) | -65.3 (20.2) | -3.0 (7.59) | -48.1 (9.26) |
| Complete residue removal-shift to manure | -71.3 (17.6) | -0.4 (12.9) | -29.3 (8.71) | -76.8 (12.20 | 17.3 (5.86) | -91.5 (33.1) | -67.7 (20.4) | -1.1 (7.60) | -70.3 (14.7) |
| Reduced Erosion | -46.0 (11.0) | 6.7 (11.3) | -15.7 (6.08) | -54.8 (8.54) | 19.2 (4.73) | -48.4 (16.1) | -29.7 (12.0) | 8.5 (6.49) | -42.2 (8.04) |
| Residue Retention | -74.4 (17.0) | -1.9 (12.6) | -6.8 (4.96) | -60.5 (51.1) | 16.4 (5.35) | -2.88 (4.94 | -53.7 (19.4) | -2.1 (7.56) | -21.7 (3.75) |

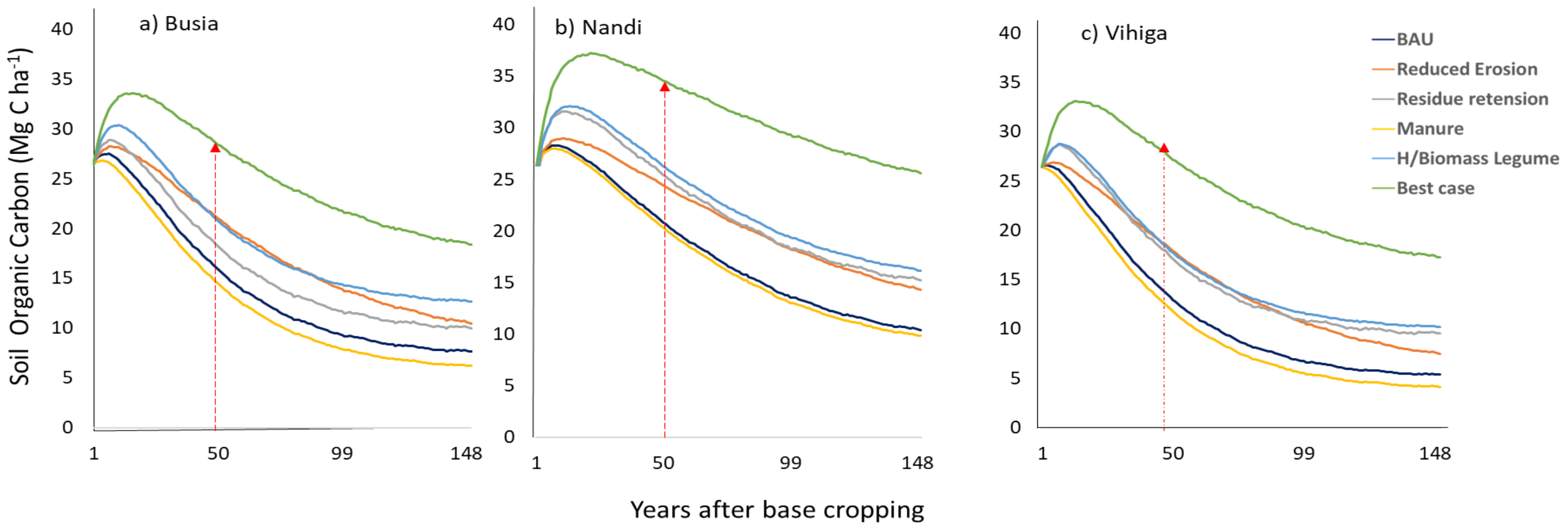

**Figure 5.6**: Total soil organic carbon after 150 years from base cropping for five scenarios: BAU (Business as usual); reduced soil erosion, 100% residue retention, Manure is the complete residue removal-shift to manure scenario where all residues are fed to livestock and returned as manures and changing from a maize- bean rotation to a maize-high biomass legume (lablab) rotation in 3 agroecological regions in western Kenya. Dashed arrow shows SOC stocks under the different scenarios at 50 years after changing from the zero-input base cropping rotation.

## 5.4 Discussion

### 5.4.1 Overall balances

In this study we undertook analysis of soil nutrient and SOC trajectories in smallholder agroecosystems of western Kenya by examining 18 case study farms. Overall, N and K balances were found to be mostly negative as reported previously in similar regions (Chianu et al., 2012; van Beek et al.,2016; Kabirigi et al., 2016). While P balances were close to zero suggesting that extensive P depletion is not occurring, this result urges caution, as subtle changes to management can easily disrupt this balance. In contrast to other studies (e.g. Zingore et al., 2007) and our own hypotheses, there were no differences in overall balances between farm types or between the main vs. secondary (least productive) fields identified by farmers. We expected Type 1 farmers, with the highest levels of resource endowment, to have positive balances at least in their main fields on N, P and K. With regard to the lack of differences in nutrient balances between main and secondary plots, we note here that there were no significant differences in management between these plots. This may be due to the fact that, contrary to other studies (e.g. Tittonell et al. 2005), the main and secondary plots are almost at equal distances from the homestead and plot sizes were similar; and it appears that farmers do not target their management to a particular field to the same extent reported by Masvaya et al. (2010) in Zimbabwe.

Our results are similar to those of Vanek and Drinkwater (2013) and Mesfin et al. (2020) who reported minimal differences between farm types (grouped by wealth) when it came to the overall balances. While the mineral fertilizer inputs and other crop nutrient inputs differ among the farm types, the overall balances are similar and do not mirror these differences. For example, in our study we note that Type 2 farmers applied more organic nutrient sources (ONS) per unit area than all the other types. In a previous study, we concluded that the reason for more use of

ONS was due to greater interaction of these farmers with farmer groups and extension, which may have led to greater importance being placed on use of ONS (Nyamasoka-Magonziwa et al., 2021). Other factors such as livestock ownership can also contribute to farmers' access to ONS (Zingore et al., 2011).

Overall balances differed between P and N, with N balances more negative than P. This finding suggests that by using small amounts of fertilizers, farmers are likely creating growing environments over time that are less P limited than N limited. However, while P balances are slightly positive, indicating that a continual accrual of P may lead these soils to gain P fertility over the longer term, in the short-term P may still be limiting in these soils due to P fixation, which is known to quite common and problematic for management in these tropical soils (Sanchez, 2019). Although P availability was highly variable among farms in a previous study in these same localities (Nyamasoka-Magonziwa et al., 2020), some fields in that study had relatively high levels of Olsen P (e.g. >15 mg $kg^{-1}$) lending some support to the possibility of P becoming less limiting over time in these tropical soils, perhaps due to increased P inputs that have created more positive P balances.

### 5.4.2 Drivers of nutrient balances

Against the backdrop of these overall balances, important conclusions can be reached by examining the dominant flows that drove these balance outcomes. We noticed a zone-to-zone variation in the organic and mineral inputs. For example, farmers in Nandi had more ONS probably due to the intensive zero-graze livestock system in this region, which allows for better management and collection of manure (Rufino et al., 2006). However, even though more organic inputs were applied in Nandi, the higher rates were not enough to yield positive balances for N and K. In the case of N, this was partly due to the high rates of erosion N losses observed in all three of the zones. The blanket recommendation of N application rates for N and P in Kenya are around 75 and 25 kg $ha^{-1}$ per season, respectively (Woomer et al., 2004) meaning that in the absence of fertilizer additions, a good manure rate (using cattle manure) would be at least 10 Mg $ha^{-1}$ $yr^{-1}$, using a 1.45 % N content of manure (more than 5 times than that is being applied in Nandi, which has the highest manure/compost rate). This recommended amount of manure/compost is unattainable for most farmers with average production being < 2 Mg $ha^{-1}$ $yr^{-1}$; Nyamasoka-Magonziwa et al., 2021). Important to consider, however, is that the blanket recommendations are not ideal as some farms may be having highly positive N and P balances already and application of too much may lead to environmental problems such as leaching of N; or some may have too negative balances that require way more than the recommended amounts. For example, rough calculations encompassing all three zones in our study suggest that manure rates of only 4 Mg $ha^{-1}$ $yr^{-1}$ would be sufficient to replace harvests and losses for N, and this amount could be reduced further if erosion was better managed, and high biomass legumes grown to contribute biologically fixed N. Greater availability of off-farm ONS through recycling of urban and periurban waste could also offset the need for manures produced on-farm and fertilizer nutrients. These varied scenarios for inputs illustrate how the mass balance approach employed here can help to develop better site-specific input requirements and can be used to examine realistic options to improve nutrient status of soils.

Mineral fertilizer use was similar among farm types despite studies by Ncube et al., (2009) and Zingore et al., (2011); indicating that wealthier farmers who can afford them often apply more fertilizers. The average mineral fertilizer application noted in this study is high compared to the average in sub-Saharan Africa (5 to 50 kg $ha^{-1}$, Roy et al., 2006; 0.9 to 16.7 kg $ha^{-1}$, Chianu et al., 2012, 15 kg $ha^{-1}$ Nyamangara et al., 2020). This high application rate, however, is not translating to good crop yields as there is poor nutrient use efficiency, likely due to the high erosion and other losses suggest by our data, as well as other production limitations such as pests, disease and drought. In addition, we note that fertilizer application was more important for N and P balances, but not K, where application rates were very low across farm locations and type.

We observed a considerable influence of nutrient losses, especially erosion, which created negative N balances, and reduced P balances to only slightly positive values. This is in line with a large number of studies that have highlighted the importance of soil erosion losses in hillslope agriculture (Vanek and Drinkwater, 2003; Montgomery, 2007). Estimated N losses from erosion in our study are quite high, for example about twice those found by Nyawade et al., (2019) in potato fields of the central Kenyan Highlands, but are comparable for P and K. Negative nutrient balances due to erosion mean that the the moderate rates of organic organic and inorganic nutrient inputs are not enough to offset the losses from erosion. This is of major concern since the three regions, especially Vihiga, experience very high rates of erosion due to steep slopes and high precipitation rates during two rainy seasons per year. Moreover, there is an increase in extreme weather events due to climate change variability in Kenya (Kogo et al., 2021), which is likely to further exacerbate nutrient loss by erosion. This nutrient loss from erosion will lead to a continued decline in soil fertility and is a major concern for food security (Roy et al., 2006), suggesting an urgent need for erosion control measures to help adapt to the adverse effects of climate change and variability.

While N and P were largely driven by erosion, K balances were more driven more by crop exports. The net negative K balances are in part due to relatively low inputs of K, and this may be related to the fact that the mineral fertilizers used are mainly N and P based (e.g., Diammonium Phosphate and Triple Super Phosphate). While a few fertilizers in the Kenyan market contain K (e.g. Mavuno and Sympal brands sold in the Western Kenya region), these were not commonly used by farmers and generally only applied to specific crops (e.g., Sympal for groundnuts). Large amounts of K in crop exports were observed in zones and farm types that have residue export. These crop exports benefit farmers in the form of crops and forage sources, so they don't really represent a 'loss'. However, the large exports lead to highly negative balances indicative of K mining. Without replenishing K through organic or mineral inputs, crop productivity and tolerance to abiotic stresses will continue to be low (Hasanuzzaman et al., 2018). This situation emphasizes the importance of residue retention, as maize stover and other crop residues are inherently high in K and are more likely to be available to farmers over K-specific fertilizer blends containing potassium.

### 5.4.3 Management scenario impacts on nutrient balances

When considering the management scenarios examined here, reducing erosion had the greatest impact on mitigating N and P losses relative to BAU. This strong impact of erosion reduction makes sense in light of the strong role of erosion as a driver in the balances (Fig. 5.5). Soil erosion by water is generally much more prevalent in uncovered, tilled soils like these case study fields, but what was clear in developing the RUSLE estimates for this region of western Kenya is that sloped land and high values of climate erosivity (estimated by a recent review and map of global erosivity data; Panagos et al., 2017) contributed greatly to the high values of erosion. As such, different management options may help to reduce the slope length and therefore controlling erosion (e.g., use of napier grass across intervals in the slope which can also offer additional forage for livestock or be applied as a soil amendment). Contour farming can also help with reduction of erosion in hilly slopes, while some have adopted a legume-hedgerow contour farming system (Hilger et al., 2013). Other options to control erosion, including intercropping with legumes such as cowpea (Nyawade et al., 2019) and retaining crop residues, especially when mulched rather than incorporated (Lal., 1995). In the reduced erosion scenario, decreasing slope length significantly reduced the nutrient losses for N and P. This is very significant considering that if the mineral fertilizers and ONS being applied by farmers are not being used efficiently and erosion is not controlled, the result is high losses. In addition to reduced yields and wasted farm resources this represents, non-point source pollution of water bodies can occur downstream from the field causing environmental degradation and health concerns associated with water quality decline (Munodawafa, 2007).

In contrast to what was observed for N and P, residue retention had the greatest impact on reducing K losses. This is because K is required in large quantities to maintain crop quality and is an important physiological/structural component of leaves and stems (Hue et al., 2020). Potassium is not exported in large quantities through grain, but is typically high in shoot and leaf tissues, so that retaining residues has more impact on K balances. Residue retention not only has the advantage of reducing nutrient exports and transfers from the plots but can offer other advantages to soil health from the added organic carbon and soil cover when left on the surface as mulch. These benefits include increased biological activity, aggregation, soil porosity, water retention and bulk density and ultimately crop productivity (Melman et al. 2019; Zhao et al., 2020). However, the challenge with residue retention in smallholder communities remains the trade-off between supporting soils vs. livestock feeding (Rodriguez; 2017).

The scenario of feeding all the crop residues to animals and applying the resulting manure to the fields created only subtle influences on N, P, and K balances compared to BAU. The increase in P balance in all locations due to manure application can be attributed to the higher P content in manure compared to the residues due to concentration of P within the flow from residues to manure as other components such as C and N are utilized to a greater degree by animals from the forage, while P remains in the manure. However, N and K balances generally suffer from the penalty of removing all crop residues, since as noted above, greater amounts of these nutrients are present in crop residues and/or are more likely to be lost in the pathway from forage to manure and during manure storage (Snijders, et al., 2009; Tittonel et al., 2010).

### 5.4.4 Soil organic carbon

Soil organic carbon is a fundamental indicator of soil health due to its influence on a wide range of critical soil functions (Doran, 2002). Stocks of SOC represent the balance of inputs through ONS and crop residues against SOC losses though decomposition and erosion in some cases (Wiesmeier et al., 2016). Because of the highly erosive conditions and continuous cultivation with two cropping cycles per year in western Kenya, all of the scenarios demonstrate a trend towards SOC decline over time, including the BAU scenario as also noted by Nyawira et al., (2019) who conducted a study on C stocks on different farming systems in western Kenya. To conserve SOC stocks, the rate of decline must be regulated through management options that either increase the organic inputs or slow down the decomposition of the SOC or losses through erosion.

In Busia, the high-biomass legume scenario and the reduced erosion scenario offered the best option to reduce SOC losses, apart from the best-case scenario where multiple strategies were implemented together in the model. However, residue retention was better at reducing SOC decline in Nandi compared to soil erosion reduction. This finding likely comes from the fact that farmers in Nandi typically only retain 25% of their crop residues in the field, and thus 100% residue retention represents a considerable change from BAU. Whereas in Busia, farmers already retain over 60 % of residues in field, so this scenario would not be expected to show as large of an impact as Nandi. In Vihiga all three of these scenarios offer a promising means to reduce SOC losses compared to BAU. These model results for the effect of residue retention accord well with Chivenge et al., (2007) who indicated that crop residues should be retained, as they are effective in building SOC stocks. The challenge however with crop residue retention is the trade-off with feeding livestock especially is zones such as Nandi and Vihiga, where there is a priority to feed crop residues to livestock rather than retaining them infield.

The positive impact of lablab in rotation found by our SOC modeling results is related to its abundant biomass production. Lablab is a multi-purpose legume that produces three to four times as much biomass as common bean (Ojiem et al.-unpublished data). When grown in rotation with maize, it contributes significantly to SOC stocks by increasing C inputs directly, promoting the increase in above and below ground maize biomass in the rotation (Diekow, 2005) and increasing the quality of residue inputs due to fixed N. Improved SOC trajectories with lablab also fit well with other results suggesting that it can increase SOC by supporting soil microbial abundance and diversity (Dörr de Quadros et al., 2019).

The scenario of reducing erosion has similar positive effects on SOC as the incorporation of lablab, and this is crucial since erosion is quite high in all the three studied regions. Studies by Nyawade et al., (2019) showed that soil erosion can cause significant SOC losses in smallholder farming systems (i.e. up to 39.5 kg C $ha^{-1}$ $yr^{-1}$ in potato fields). This is why reducing the slope length and creation of contoured live barriers can result in significantly reduced SOC losses in a way that takes account of farmers' ability to implement these, and ideally with levels of incentives and technical support.

As expected, a best-case scenario which combines three promising management options led substantial mitigation of declining SOC, suggesting that multiple soil conservation practices (especially those that also serve other beneficial functions for farmers such as forage production) may need to be applied in unison effectively slow SOC loses over time. However, adopting all three may be a formidable task for farmers in terms of labor, time and new knowledge required to implement these practices (Tetteh, 2021) and so options for adopting at least one, two or all three practices should be encouraged. Furthermore, calls to look beyond the strategies modelled here to find other methods that increase C inputs and reduce C losses that can be easily adopted by farmers should be encouraged (Reiji et al., 2013).

The complete residue removal + manure scenario performed worse than BAU in terms of building SOC. This scenario suffered from penalties of removing all crop residues and returning half of them as manure, with clear losses of C in the cycle from the field through the animal and back to the field. This shows further the importance of retaining all or at least some residues in the field to reduce SOC decline. It also suggests the need to access new forms of off-field and off-farm residues, forages, manure, and other ONS to complement the manure produced on the farm.

## 5.5 Conclusions

Nitrogen and K balances on 18 studied farms were largely negative across location and farm types, while P balances were closer to zero or slightly positive. The major drivers of N and P balances are mineral fertilizer input, crop export and erosion rates (which are very high in the three zones). This gives an urgent reason to find ways that are appropriate for smallholder farmers in the region to control erosion as well as manage added nutrients better. Potassium balances are mainly driven by crop residue exports, but concern is raised over the low replacement of exported K since the main fertilizers used do not contain K and the residues largely exported off farm. There is a need to emphasize residue retention to reduce K losses and/or to include K containing inputs in form of fertilizers and manures to replenish K losses. The scenarios examined here indicate that retaining residues as well as reducing erosion have the potential to effectively reduce nutrient losses as well as improve C stocks, meaning management strategies that encourage crop residue retention and deliberate soil erosion control should be encouraged. Feeding all residues to animals and applying the produced manure on the other hand did not influence nutrient balances or C stocks positively, as the produced manure provided too low an application rate to be effective. As such, manure should be applied to compliment residue retention and alternative feed sources such as napier grass explored to still have residues retained and animals fed. Including a high biomass yielding legume such as lablab in rotation with maize in place of a low biomass yielding common bean has the benefit of raising the SOC stocks. When all three positive practices were combined in a 'best case' scenario (reduced erosion, residue retention and high biomass) this showed potential to double SOC compared to the current practices in the three locations, over a time horizon of 50 years. However, given that this might not be attainable by most farmers, practicing at least one of the scenarios will still contribute to better outcomes for soil health.

## 5.6 References

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# CHAPTER 6: SUMMARY

This dissertation intended to validate a Soil Tool Kit against standard lab measures as well as to understand the drivers of management practices for organic nutrient sources and the resulting implications for soil health in smallholder farming communities in western Kenya. My study showed that there are various factors that influence the management of soil health in smallholder farming contexts and emphasized the need for interdisciplinary research in understanding agricultural systems (Balch et al., 2020).

Firstly, my study showed that an in-field tool kit assembled for quantitative soil analysis in smallholder farming systems can be useful in providing site-specific measures of soil health indicators. We noted that POXC and pH measured with the tool kit from Kenyan soils were highly correlated to those measured by a standard laboratory ($R^2$=0.77; R2=0.56; respectively). The tool kit and standard laboratory available P were less well correlated, but also showed a highly significant positive relationship ($R^2$=0.30). Similar patterns were noted for POXC, pH and available P measured in Peruvian soils ($R^2$=0.75; $R^2$=0.75; $R^2$=0.35; respectively). Importantly, the tool kit and standard lab analyses also displayed similar abilities to predict maize grain yield in Kenya. When used to detect soil impacts of incorporating P. vulgaris versus L. *purpureus*, only POM differed significantly between the two legume treatments, although L. *purpureus* was slightly higher for most of the beneficial soil health properties.

Secondly, my findings indicated that, there was greater stabilization of shoot derived C in the mineral associated organic matter fraction (twice as much as manure and 1.63 times more than ex-situ roots C). In addition, additions of N, P and S, designed to balance the stoichiometry of inputs to reflect the stable fine fraction of SOM (C: N:P:S-10,000:833:200:143) did not result in greater C stabilization as anticipated, and as suggested by Kirkby et al. (2013).

Thirdly, I hypothesized that resource endowment together with key socio-cultural variables (e.g., gender, network connections, adherence to social norms, extension, training) and biophysical aspects, such as differences in agroecological contexts (location - which influences climate, soils, and farming systems and perceived soil fertility), significant determinants of organic nutrient sources (ONS) management. My findings validate the importance of resource endowment and wealth proxies as well as perceived plot soil fertility in influencing ONS use building on past research (Chikowo et al., 204) but also shed light on several other important factors. Land tenure had an important influence, in which main fields not owned by farmers were more likely to retain residues. In addition, management of residues depended on gender, seen especially in the burning of legume residues for alternate and preferred uses by women farmers and notable since these higher quality residues are often considered key to sustainable soil nutrient management. Farm type was associated with resource endowment and connectedness of farms to extension and other farmers and influenced the allocation of cattle and poultry manure and maize residues. Finally, there was a strong overarching influence of agroecological zone on the allocation of ONS.

Lastly, I intended to evaluate the current N, P, K and C flows for a number of representative surveyed farms in in western Kenya to determine the main drivers of nutrient balances and C stocks and predict how different management interventions will influence nutrient balances and SOC in the long-term. My results showed that net N, P and K balances were highly variable across all farms but were on average negative. Agroecological location of farm, farm typology and field type did not affect the overall nutrient balances but there were some differences in the input and output sources between the locations and farm types. Erosion rate played a major role in overall nutrient balances. Reducing erosion scenario had the greatest impact on mitigating N and P losses relative to BAU. Residue retention had the greatest impact on K balances especially in Nandi. Removing all residues + manure scenario did not have a high impact on the balances in all locations. As for soil C stocks, removing all residues + manure and business as usual BAU led to the lowest C stocks in all regions. Reduced erosion, residue retention and high biomass legume scenarios all resulted in at least 50 % more SOC after 50 years from base cropping compared to BAU. The best-case scenario which combined Reduced erosion, residue retention and high biomass legume resulted in at least 200 % more C stocks across zones.

In summary, my findings suggest that the tool kit methods proposed have broad applicability to smallholder farms for explaining variability in crop yields, assessing soil contexts, and quantifying management-induced changes in soil health. This will help in scaling out useful soil analysis in smallholder farming communities. My study highlights the potential importance of residue retention as a strategy to increase soil C content and therefore soil health and did not support that N, P, and S additions increased C stabilization in MAOM over the long-term. Residues are also seen to maintain N and P balances and to increase soil C stocks as agreed on in other studies. Other management strategies to improve SOC include the incorporation of a high biomass legume such as lablab in rotation with maize instead of a low biomass legume such as common bean. In addition, given the interplay of socio-economic, environmental, and socio-cultural factors in influencing ONS management organizations and extension agents working with farmers on soil fertility management need to understand these factors so that they can better tailor strategies, trainings and capacity building efforts related to the use of ONS. For example, given the important role women play in managing legume residues, engaging only with males in households regarding the benefits or challenges of legume residue management is likely to be far less effective than engaging with a variety of household members. Furthermore, exploring the balances based on the inputs and outputs of different zones and farm types will enable a site specific, context-based strategy of managing nutrients as the balances are highly variable within the farm and zones to allow for responsible nutrient management (Johnston and Bruulsema, 2014).

As research and development organizations continue to engage with smallholder farmers to reduce the burden of global food insecurity, the insights gained by this research will allow better anticipation of drivers and obstacles to improved nutrient management in these farming landscapes and communities for enhanced soil health and crop productivity.

## 6.1 References

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