



# Organic Nutrient Source Allocation and Use in Smallholder Farming Communities: What Are We Missing?

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Organic nutrient sources (ONS) are managed as a key resource by smallholder farmers to maintain the productivity of soils. Recycling of ONS by applying them to soils is a globally dominant strategy of ecological nutrient management. Understanding how ONS produced on-farm are allocated and what drives farmer decision making around their use is critical for sustainable nutrient management in smallholder agroecosystems. Using focus group discussions and a survey of 184 farming households, we studied socio-economic, socio-cultural, and environmental drivers of ONS allocation and use at the farm scale in three contrasting agroecological zones of western Kenya. Farm typologies of ONS management were also developed using cluster analysis based on resource endowment and the connectedness of farmers, management norms, and interaction with extension. Our findings suggest that the more resource endowed a farmer is, the more ONS are allocated to the main plot within the farm. We also observed that farmers preferred allocating more resources to plots that were considered more fertile. Land tenure had an important influence, in that main plots not owned by farmers were more likely to retain ONS such as crop residues. Management of residues is dependent on farmer gender, for instance, female farmers tended to burn legume residues in particular, which is notable since these higher quality residues are often considered key to sustainable soil nutrient management. Farm typologies featured different allocation patterns of ONS and were associated with resource endowment and farmer networks, including external ties to extension agents and internal ties to other farmers. Finally, there was a strong overarching influence of agroecological zone that often escapes characterization on the allocation of ONS. 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.

**Keywords:** soil health, cereal-legume-livestock systems, crop residues, manure, socio-cultural, ecological nutrient management

## INTRODUCTION

On many smallholder farms around the world, crop yields remain low (i.e., around  $1 \text{ Mg ha}^{-1}$  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 SDG2 targets.

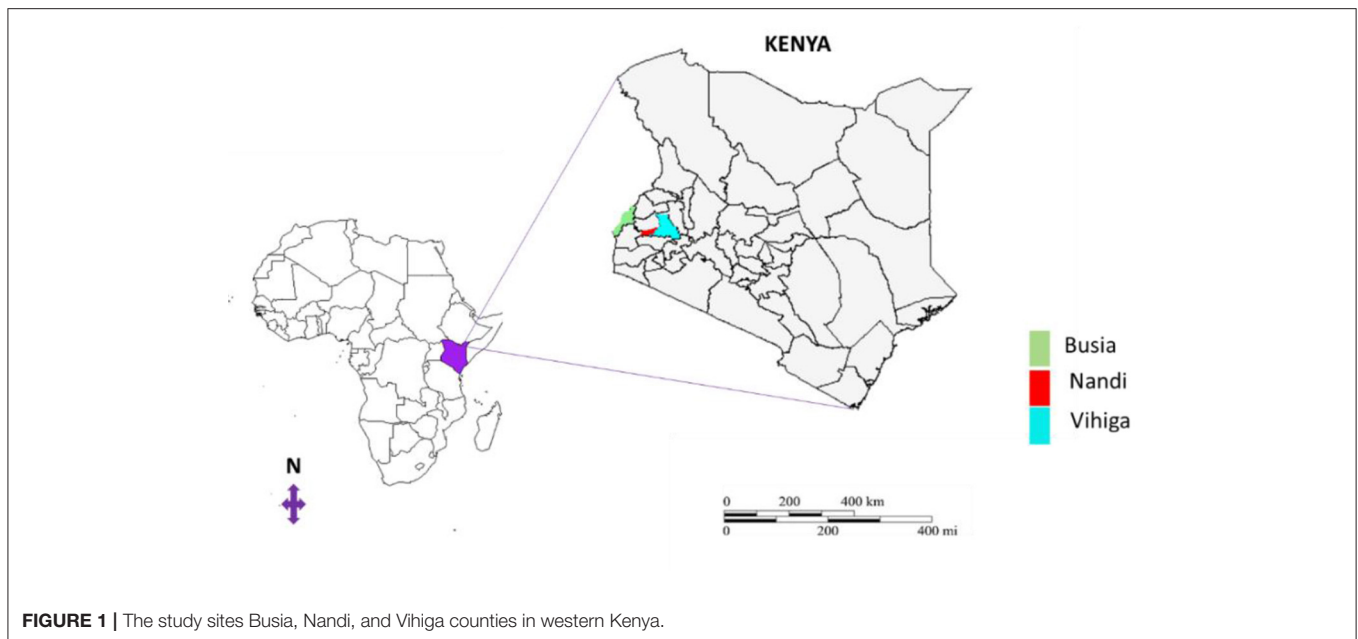
Smallholder farmers produce and manage organic resources such as crop residues (Valbuena et al., 2012; Turmel et al., 2015), animal manure (Rufino et al., 2007) and farmyard manure/compost on farm. They may also collect off-farm organic resources, such as forest litter or plant residues from field margins, 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 (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 (Vanlauwe et al., 2007; Zingore 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 et al., 2006). 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 (Tittonell et al., 2005; Kolawole, 2013) 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.

## METHODOLOGICAL APPROACH

### Study Sites

The study was carried out in western Kenya in the counties of Nandi, Busia, and Vihiga (Figure 1). Located in different agroecological zones, the three counties experience distinct climates (Table 1) and have unique farming systems.

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 (Agriculture Organization for the United Nations, 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

**TABLE 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	1,165	22.4	1,239	Aw and Am-tropical savanna
Nandi	0° 10' 0" N, 35° 9' 0" E	1,984	17.4	1,551	Cfa-Humid subtropical and Af-tropical rainforest
Vihiga	0° 4' 0" N, 34° 40' 0" E	1,643	20.0	1,921	Af-tropical rainforest

\*Köppen-Geiger Rohli et al. (2015).

**TABLE 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 ( <i>Zea mays</i> )	0.89	0.08	2.78	Okalebo et al., 2002
	common bean residues ( <i>Phaseolus vulgaris</i> )	1.2	0.13	2.06	
	Napier grass ( <i>Pennisetum purpureum</i> )	1.02	0.11	2.63	
	Lablab ( <i>Lablab purpureus</i> ) prunings	1.31	0.33	-	
Manures	Cattle manure fresh/composted	1.12	0.3	2.38	Lekasi et al., 2003
	Poultry manure	3.11	0.42	2.40	Okalebo et al., 2002
	Farmyard manure	1.81	0.3	0.9	unpublished data
	Compost	1.34	0.20	1.82	Okalebo et al., 2002
Others	Biochar	0.56	0.03	0.73	unpublished data
	<i>Tithonia diversifolia</i> prunings	3.5	0.37	4.1	Jama et al., 2000

(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 (Tittonell et al., 2009; Sorre, 2017; Oduor et al., 2019). 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 2).

## Study Approach

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

## 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 h 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.

## 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 and survey instrument in Supplementary Material).

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 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). 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).

### 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 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% of 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).

### Estimation of ONS Produced on Farm

Average total organic inputs were estimated for maize crop yields from farmer reported maize yield ( $\text{Mg ha}^{-1}$ ) 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 ( $\text{kg DM season}^{-1}$ ) 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 =  $\sim 20 \text{ kg day}^{-1} \text{ animal}^{-1}$  (Nennich et al., 2005)] and poultry =  $\sim 0.13 \text{ kg day}^{-1} \text{ animal}^{-1}$  (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.

### 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 et al., 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.

### 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

**TABLE 3** | Household demographic information and farm characteristics of smallholder farmers interviewed in Nandi, Busia, and Vihiga counties in western Kenya in June 2019.

Location	Busia (n = 60)	Nandi (n = 62)	Vihiga (n = 62)
<b>Number of households per category</b>			
<b>Gender of household head</b>			
Female	13	19	15
Male	47	43	48
<b>Household size (no. of members)</b>			
2 or less	2	1	1
2–5	12	15	18
5–9	35	33	40
>10	11	13	4
<b>Food sufficiency (months)*</b>			
12	16	10	13
8–11	26	18	18
5–7	9	8	15
<5	9	26	17
<b>Livelihood strategies</b>			
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
<b>Education of household head</b>			
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
<b>Mineral fertilizer use</b>			
No	10	7	6
Yes	50	55	56
<b>Tenure of main plot</b>			
Owned	49	55	49
Rented/shared	11	7	13
<b>Farm characteristics - Mean (SE)</b>			
Livestock ownership (TLU) <sup>‡</sup>	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.

<sup>‡</sup>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).

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 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.

## RESULTS

### 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 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

**TABLE 4** | 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 <sup>-1</sup> ) <sup>‡</sup> 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 <sup>λ</sup>
Response	Allocation and use of organic inputs to the main plot <sup>†</sup>	% 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).

<sup>‡</sup>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.

<sup>λ</sup>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.

<sup>†</sup>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).

**TABLE 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 2. "I prefer feeding our livestock first and what remains I can take to the field" Vihiga farmer 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" 5. "The decision to burn legume residues is usually made by female members of the household" 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/20 kg bag." 8. "I can exchange maize stalks for milk" 9. "I can fetch more money from selling milk, so I prefer giving the residues to my livestock" 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)"

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).

## 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

**TABLE 6** | Characterization of farming systems and organic input use in the main plots vs. secondary plots in smallholder systems from western Kenya.

		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/Rented/Shared	83% 17%	73% 27%	0.001*
Main farming system	Mixed/intercropping/Sole cropping/Fallow	75% 24% 1%	40% 46% 14%	0.004‡
Organic input use in plot	Yes/No	78% 22%	44% 56%	0.005‡
Average yield-2018 long rainy season (Mg ha <sup>-1</sup> )	Maize/Beans	1.03 0.44	0.44 0.46	0.001* 0.04*

p-values for differences between means of the main and secondary plots are shown in the far-right column.

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

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

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 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 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 6).

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.

## Gender and Organic Nutrient Source Management

The general allocation and management responsibility of organic resources by gender depended on the type of ONS (Figure 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 (Figure 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  $\pm$  standard error:  $55 \pm 6.7\%$ ;  $n = 137$ ) than female headed households ( $39 \pm 3.9\%$ ;  $n = 46$ ).

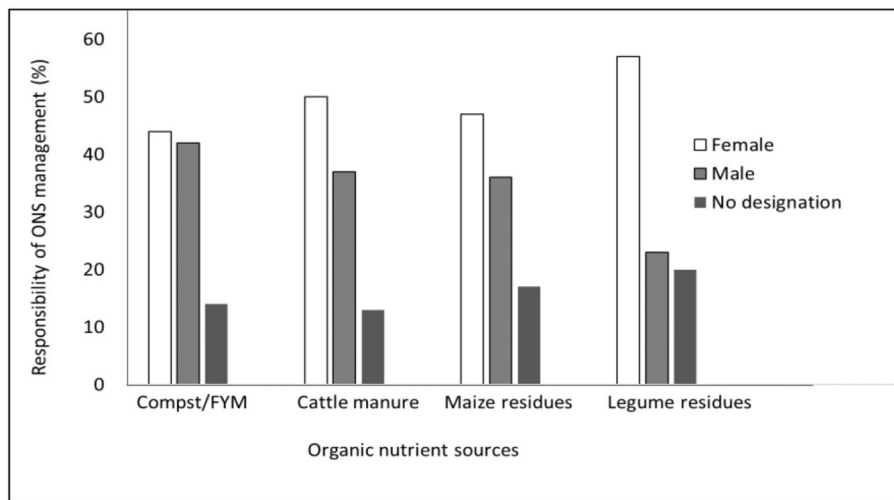
## Zone to Zone Variation in Organic Nutrient Source Allocation

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 (Figure 3). Farmers in Nandi and Vihiga were more likely to feed crop residues to livestock than retain them in the field. The proportion of crop residues allocated to the main plot vs. other fates also differed between locations ( $p < 0.001$ ; Table 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 ( $67.33 \pm 4.53\%$ ) plot than that observed in Nandi and Vihiga ( $39.9 \pm 3.5\%$ ;  $29.51 \pm 3.73\%$ ). 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 7) with farmers in Busia and Vihiga allocating a higher proportion of the manure produced to the main plot ( $51.3 \pm 5.4\%$ ,  $49.8 \pm 5.3\%$  vs.  $32.3 \pm 5.3\%$  in Busia, Vihiga, and Nandi, respectively).

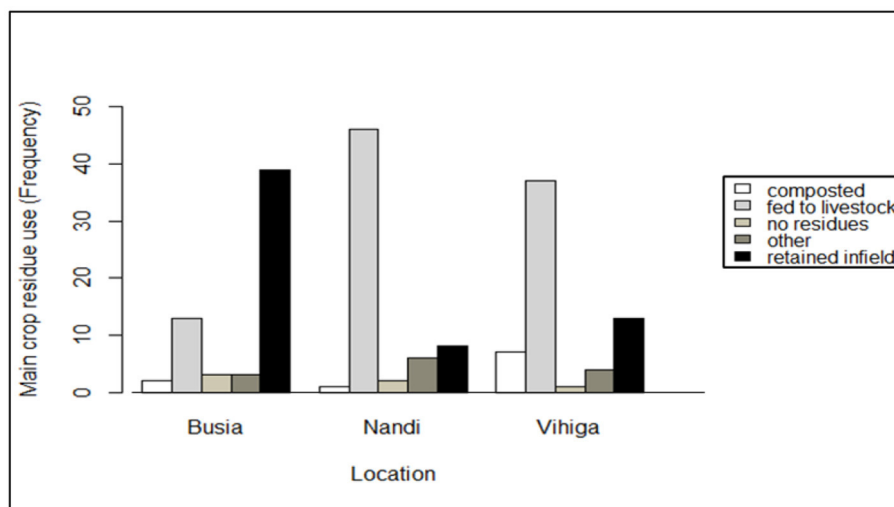
## Resource Endowment Factors

A variety of farm resource indicators influenced allocation of ONS to the main plot as an indicator of nutrient management strategies (Table 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





**FIGURE 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.



**FIGURE 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.

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 =  $22\% \pm 5.3$ ;  $n = 33$ ) compared to households that were less food secure (average proportion allocated to the main plot  $51\% \pm 7.33$ ;  $n = 36$ ;  $p = 0.02$ ; **Table 7**). Regarding land tenure, farmers who rented or shared plots retained significantly more residues (owned  $39.28\% \pm 2.76$  vs. shared/rented  $59.03\% \pm 6.3$ ;  $t$ -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.

### Socio-Cultural Factors as Drivers of ONS Management

Adherence to social norms helped to explain some of the variability in ONS management (**Table 7**). However, adherence to norms of crop residue management appeared to depend on location (adherence to norms by location interaction:  $p = 0.04$ ; **Table 8**). Overall, farmers who indicated adherence to social norms of crop residue management in Vihiga retained

**TABLE 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.

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 <sup>‡</sup>	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 <sup>-1</sup> )	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

Data was collected from 184 households in June of 2019.

\*Are predictor variables selected in the final model following stepwise regression analysis. TLU are Tropical Livestock Units (TLU).

<sup>‡</sup>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.

**TABLE 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  $n = 60$ ).

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 (6.75) <sup>d</sup>	65.2 (6.73) <sup>cd</sup>	50.0 (13.09) <sup>abcd</sup>	57.8 (12.94) <sup>b</sup>	18.3 (8.10) <sup>a</sup>	31.9 (9.71) <sup>ab</sup>
Nandi	27.7 (8.06) <sup>ab</sup>	33.5 (3.68) <sup>ab</sup>		37.8 (12.94) <sup>b</sup>	40.0 (11.71) <sup>a</sup>	42.4 (7.21) <sup>ab</sup>
Vihiga	45.6 (7.07) <sup>bc</sup>	19.1 (3.04) <sup>a</sup>		100 (38.8) <sup>b</sup>	26.2 (7.21) <sup>a</sup>	26.7 (8.47) <sup>ab</sup>
<i>p values</i>	Adherence: $p = 0.003$			Adherence: $p = 0.04$		
	Location: $p = <0.001$			Location: ns		
	Adherence x Location: $p = 0.04$			Adherence x Location: ns		

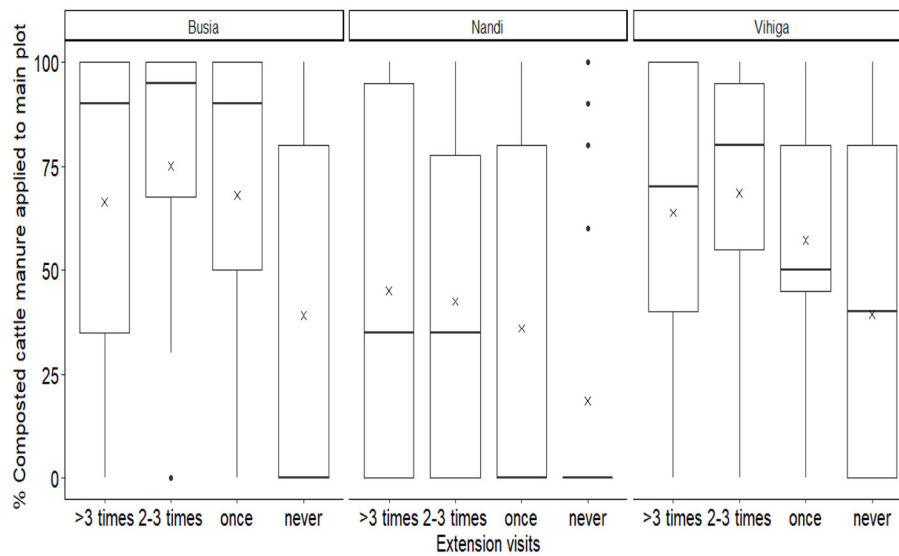
Means connected by the same letter are not significantly different using Tukey's HSD pairwise comparisons. Numbers in parenthesis are the standard error of the mean.

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 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  $52\% \pm 10.6$ ;  $n = 19$ ) compared to those that were not sure of composting norms (average proportion applied to main plot:  $36\% \pm 4.9$ ;  $n = 64$ ) and those who adhered composting norms (average proportion applied to main plot:  $25\% \pm 4.7$ ;  $n = 62$ ).

Extension visits were significantly correlated with the proportion of composted cattle manure allocated to the main plot ( $p = 0.002$ ; **Table 7**). Overall, farmers who had never been visited by extension (99 out of 184 farmers) allocated ~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 (**Figure 4**).



**FIGURE 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.

**TABLE 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.

Farm type	n	Description
1	28	<b>Resource endowed</b> 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	<b>Non-adherent and well-connected</b> 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	<b>Adherent and less connected</b> 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	<b>Least resource endowed</b> 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.

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.

## 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 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).

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<sup>-1</sup>) 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.

**TABLE 10** | Mean total organic inputs by farm type produced by farming households ( $n = 184$ ) during a typical long rainy season in western Kenya.

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

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.

Type 1 farmers had significantly more estimated manure production per season (1,639 kg season<sup>-1</sup>) compared to all the other farmers (Table 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 10).

Small quantities of poultry manure were produced by farmers and did not differ significantly among types (Table 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.

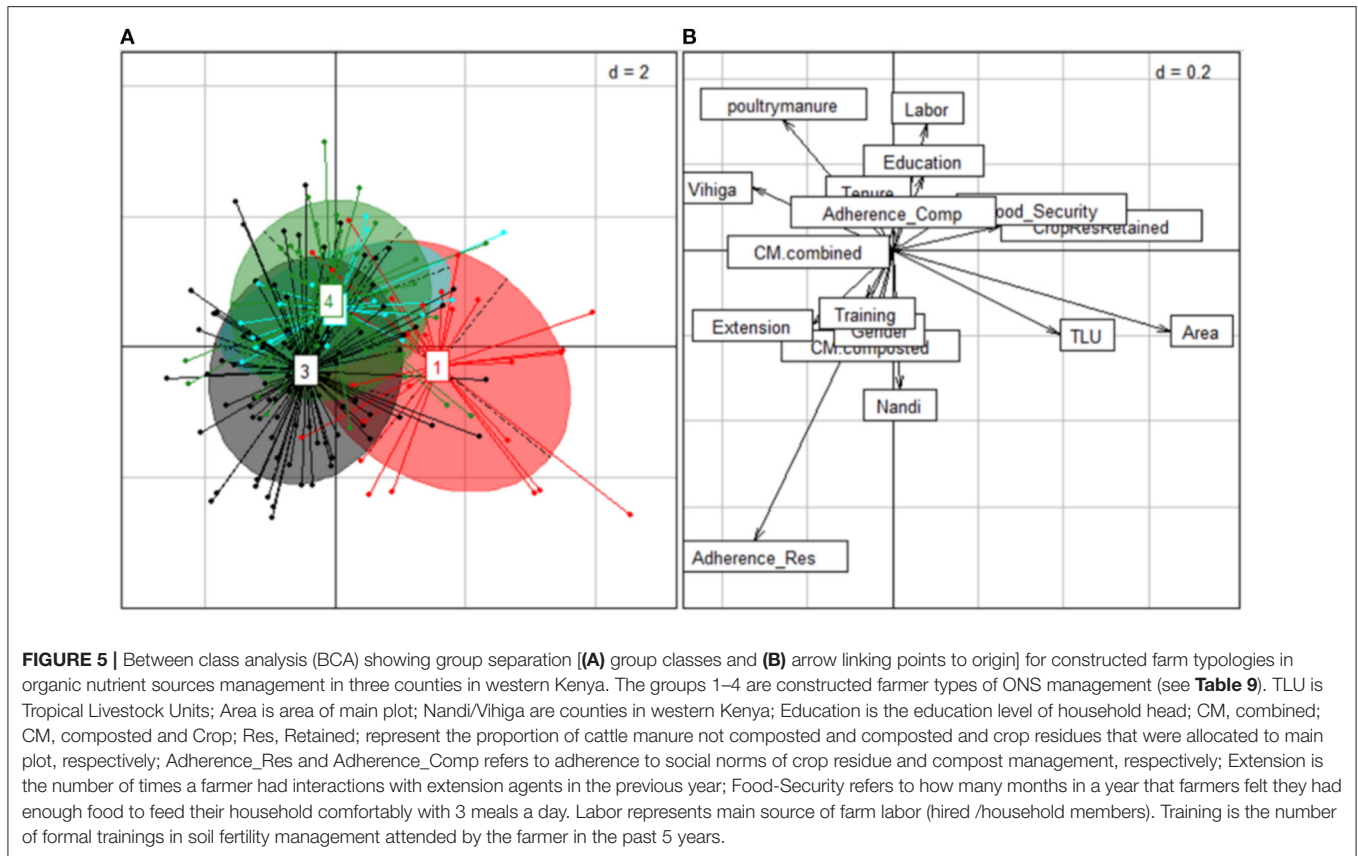
Consultation with other farmers on issues concerning soil fertility and organic nutrient sources management was

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 (Figure 5), and highly significant differences among the four farmer types (Monte-Carlo test  $p = 0.001$ ). Nevertheless, there was some overlap between farm types (Figure 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.

## 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 (Mugwe et al., 2009; Andrews et al., 2013; Ajayi and Solomon, 2017), but also indicate some divergent or interesting additional patterns in allocation of ONS in smallholder farms of this region.



## 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**; **Figure 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 in-field, 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.

## 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 vs. 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 (Pedzisa et al., 2015; Rusinamhodzi et al., 2016). 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; Tittone et al., 2005; Masvaya et al., 2010; Giller et al., 2011). 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.

## 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 and Kerr, 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 (Adjei-Nsiah et al., 2004; Fraser, 2004; Lawin and Tamini, 2019). 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.

## 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, Faniyi 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 (Pedzisa et al., 2015; Ajayi and Solomon, 2017). 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.

## 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).

## CONCLUSIONS

Our findings indicate that beyond resource endowment (livestock, land area, labor), additional factors of location, perceived soil fertility of a 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.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Colorado State University Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

## AUTHOR CONTRIBUTIONS

BN-M, SV, and SF conceived of the presented idea. BN-M developed the instruments with the contributions from MC and JO. BN-M analyzed the data with contributions from SV. SF supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

## REFERENCES

- Adjei-Nsiah, S., Leeuwis, C., Giller, K. E., Sakyi-Dawson, O., Cobbina, J., Kuyper, T. W., and Van Der Werf, W. (2004). Land tenure and differential soil fertility management practices among native and migrant farmers in Wenchi, Ghana: implications for interdisciplinary action research. *NJAS-Wageningen J. Life Sci.* 52, 331–348. doi: 10.1016/S1573-5214(04)80020-4
- Adolwa, I. S., Schwarze, S., Waswa, B., and Buerkert, A. (2019). Understanding system innovation adoption: A comparative analysis of integrated soil fertility management uptake in Tamale (Ghana) and Kakamega (Kenya). *Renew. Agricult. Food Syst.* 34, 313–325. doi: 10.1017/S1742170517000485
- Agegehu, G., and Amede, T. (2017). Integrated soil fertility and plant nutrient management in tropical agro-ecosystems: a review. *Pedosphere* 27, 662–680. doi: 10.1016/S1002-0160(17)60382-5
- Agriculture Organization for the United Nations (1998). World Reference Base for Soil Resources (No. 84). *Food Agric. Org.* Available online at: <http://www.fao.org/3/W8594E/w8594e00.htm#Contents> (accessed January 18, 2019).
- Ajayi, M. T., and Solomon, O. (2017). *Influence of Extension Contact and Farmers' Socio-Economic Characteristics on Adoption of Oil Palm Technologies in Aniocha North Local Government, Delta State*. Nigeria. Available online at: <http://hdl.handle.net/123456789/2543> (accessed April 3, 2021).
- Akaike, H. (1987). *Factor Analysis and AIC*. In *Selected Papers of Hirotugu Akaike*. New York, NY: Springer. doi: 10.1007/978-1-4612-1694-0\_29
- Alvarez, S., Timler, C. J., Michalscheck, M., Paas, W., Descheemaeker, K., Tittonell, P., et al. (2018). Capturing farm diversity with hypothesis-based typologies: An innovative methodological framework for farming system typology development. *PLoS ONE* 13:194757. doi: 10.1371/journal.pone.0194757
- Andrews, A. C., Clawson, R. A., Gramig, B. M., and Raymond, L. (2013). Why do farmers adopt conservation tillage? An experimental investigation of framing effects. *J. Soil Water Conserv.* 68, 501–511. doi: 10.2489/jswc.68.6.501
- Balch, J. K., Iglesias, V., Braswell, A. E., Rossi, M. W., Joseph, M. B., Mahood, A. L., et al. (2020). Social-environmental extremes: Rethinking extraordinary events as outcomes of interacting biophysical and social systems. *Earth's Future* 8:e2019EF001319. doi: 10.1029/2019EF001319
- Bougeard, S., and Dray, S. (2018). Supervised Multiblock Analysis in R with the ade. *J. Stati. Softw.* 86:17. doi: 10.18637/jss.v086.i01
- Carolan, M. S. (2006). Social change and the adoption and adaptation of knowledge claims: Whose truth do you trust in regard to sustainable agriculture? *Agric. Human Values* 23, 25–339. doi: 10.1007/s10460-006-9006-4
- Caulfield, M. E., Fonte, S. J., Tittonell, P., Vanek, S. J., Sherwood, S., Oyarzun, P., et al. (2020). Inter-community and on-farm asymmetric organic matter allocation patterns drive soil fertility gradients in a rural Andean landscape. *Land Degrad. Dev.* 31, 2973–2985. doi: 10.1002/ldr.3635
- Chavent, M., Kuentz-Simonet, V., Labenne, A., and Saracco, J. (2014). *Multivariate Analysis of Mixed Data: The PCAMixdata R Package*. Available online at: 1411.4911.pdf (arxiv.org) (accessed July 7, 2019).
- Chikowo, R., Zingore, S., Snapp, S., and Johnston, A. (2014). Farm typologies, soil fertility variability and nutrient management in smallholder farming in Sub-Saharan Africa. *Nutr. Cycl. Agroecosyst.* 100, 1–18. doi: 10.1007/s10705-014-9632-y
- Chilonda, P., and Otte, J. (2006). Indicators to monitor trends in livestock production at national, regional and international levels. *Livestock Res. Rural Dev.* 18:117. Available online at: <http://www.lrrd.org/lrrd18/8/chil18117.htm> (accessed December 15, 2020).
- Croissant, Y. (2020). *mlogit: Multinomial Logit Models. R package version 1.0-2.1*. Available online at: <https://CRAN.R-project.org/package=mlogit> (accessed February 25, 2021).
- Dawadi, D. R., and Sah, S. K. (2012). Growth and yield of hybrid maize (*Zea mays* L.) in relation to planting density and nitrogen levels during winter season in Nepal. *Trop. Agricult. Res.* 23, 218–227. doi: 10.4038/tar.v23i3.4659
- Daxini, A., O'Donoghue, C., Ryan, M., Buckley, C., Barnes, A. P., and Daly, K. (2018). Which factors influence farmers' intentions to adopt nutrient management planning? *J. Environ. Manage.* 224, 350–360. doi: 10.1016/j.jenvman.2018.07.059
- DeVault, M. L. (1994). *Feeding the Family: The Social Organization of Caring as Gendered Work*. Chicago, IL: University of Chicago Press.
- Duncan, A. J., Bachewe, F., Mekonnen, K., Valbuena, D., Rachier, G., Lule, D., et al. (2016). Crop residue allocation to livestock feed, soil improvement and other uses along a productivity gradient in Eastern Africa. *Agric. Ecosyst. Environ.* 228, 101–110. doi: 10.1016/j.agee.2016.05.011
- Faniyi, E. O., Deji, O. F., Oyedele, D. J., and Adebooye, O. C. (2019). Gender assessment of vegetable farmers' utilisation of soil and water conservation technologies in MicroVeg project sites, southwest Nigeria. *Acta Horticulturae* 239–248. doi: 10.17660/ActaHortic.2019.1238.25
- Ferguson, A. E. (1994). Gendered science: a critique of agricultural development. *Am. Anthropol.* 96, 540–552. doi: 10.1525/aa.1994.96.3.02a00060
- Ferraro, M. B., Giordani, P., and Serafini, A. (2019). fclust: an R package for fuzzy clustering. *R J.* 11, 198–210. doi: 10.32614/RJ-2019-017
- Fisher, M., Holden, S. T., Thierfelder, C., and Katengeza, S. P. (2018). Awareness and adoption of conservation agriculture in Malawi: what difference can farmer-to-farmer extension make? *Int. J. Agricult. Sustainab.* 16, 310–325. doi: 10.1080/14735903.2018.1472411

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2021.692981/full#supplementary-material>



- Folke, C., Carpenter, S., Elmqvist, T., Gunderson, L., Holling, C. S., and Walker, B. (2002). Resilience and sustainable development: building adaptive capacity in a world of transformations. *AMBIO: J Hum Environ.* 31, 437–440. doi: 10.1579/0044-7447-31.5.437
- Fox, J., and Monette, G. (1992). Generalized collinearity diagnostics. *J. Am. Stat. Assoc.* 87, 178–183. doi: 10.1080/01621459.1992.10475190
- Franzel, S., Sinja, J., and Simpson, B. (2014). Farmer-to-farmer extension in Kenya: the perspectives of organizations using the approaches. *World Agroforest. Center Working Paper* 181:14380. doi: 10.5716/WP14380.PDF
- Fraser, E. D. (2004). Land tenure and agricultural management: soil conservation on rented and owned fields in southwest British Columbia. *Agric. Human Values* 21, 73–79. doi: 10.1023/B:AHUM.0000014020.96820.a1
- Giller, K. E., Tittonell, P., Rufino, M. C., Van Wijk, M. T., Zingore, S., Mapfumo, P., et al. (2011). Communicating complexity: integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. *Agric. Syst.* 104, 191–203.
- Grabowski, P. P., and Kerr, J. M. (2014). Resource constraints and partial adoption of conservation agriculture by hand-hoe farmers in Mozambique. *Int. J. Agric. Sustainability* 12, 37–53. doi: 10.1080/14735903.2013.782703
- Hair, J. F., Black, W. C., Babin, B. J., Anderson, R. E., and Tatham, R. L. (1998). *Multivariate Data Analysis*. Upper Saddle River, NJ: Prentice hall.
- Harvard Humanitarian Initiative (2018). Available online at: <https://www.kobotoolbox.org/> (accessed March 6, 2019).
- Jama, B., Palm, C. A., Buresh, R. J., Niang, A., Gachengo, C., Nziguheba, G., and Amadalo, B. (2000). Tithonia diversifolia as a green manure for soil fertility improvement in western Kenya: a review. *Agroforest. Syst.* 49, 201–221. doi: 10.1023/A:1006339025728
- Jayakaran, R. I. (2002). *The Ten Seed Technique*. World Vision International. Available online at: <https://www.participatorymethods.org/resource/ten-seed-technique-0> (accessed May 23, 2019).
- Khalid, S., Khan, H. A., Arif, M., Altawaha, A. R., Adnan, M., Fahad, S., et al. (2019). “Organic matter management in cereal based system: Symbiosis for improving crop productivity and soil health,” in *Sustainable Agriculture Reviews*, eds R. Lal and R. Francaviglia (Cham: Springer). doi: 10.1007/978-3-030-26265-5\_3
- Kolawole, O. D. (2013). Soils, science and the politics of knowledge: How African smallholder farmers are framed and situated in the global debates on integrated soil fertility management. *Land Use Policy* 30, 470–484. doi: 10.1016/j.landusepol.2012.04.006
- Kristjanson, P., Bryan, E., Bernier, Q., Twyman, J., Meinzen-Dick, R., Kieran, C., et al. (2017). Addressing gender in agricultural research for development in the face of a changing climate: where are we and where should we be going? *Int. J. Agric. Sustainab.* 15, 482–500. doi: 10.1080/14735903.2017.1336411
- Lalani, B., Dorward, P., Holloway, G., and Wauters, E. (2016). Smallholder farmers’ motivations for using Conservation Agriculture and the roles of yield, labour and soil fertility in decision making. *Agric. Syst.* 146, 80–90. doi: 10.1016/j.agsy.2016.04.002
- Lawin, K. G., and Tamini, L. D. (2019). Land Tenure Differences and Adoption of Agri-Environmental Practices: Evidence from Benin. *J. Dev. Stud.* 55, 177–190. doi: 10.1080/00220388.2018.1443210
- Lekasi, J. K., Tanner, J. C., Kimani, S. K., and Harris, P. J. C. (2003). Cattle manure quality in Maragua District, Central Kenya: effect of management practices and development of simple methods of assessment. *Agric. Ecosyst. Environ.* 94, 289–298. doi: 10.1016/S0167-8809(02)00037-3
- Leonhardt, H., Penker, M., and Salhofer, K. (2019). Do farmers care about rented land? A multi-method study on land tenure and soil conservation. *Land Use Policy* 82, 228–239. doi: 10.1016/j.landusepol.2018.12.006
- Liu, T., Bruins, R. J., and Heberling, M. T. (2018). Factors influencing farmers’ adoption of best management practices: A review and synthesis. *Sustainability* 10:432. doi: 10.3390/su10020432
- Lu, X. (2020). A meta-analysis of the effects of crop residue return on crop yields and water use efficiency. *PLoS ONE* 15:e0231740. doi: 10.1371/journal.pone.0231740
- Masvaya, E. N., Nyamangara, J., Nyawasha, R. W., Zingore, S., Delve, R. J., and Giller, K. E. (2010). Effect of farmer management strategies on spatial variability of soil fertility and crop nutrient uptake in contrasting agro-ecological zones in Zimbabwe. *Nutr. Cycl. Agroecosyst.* 88, 111–120. doi: 10.1007/s10705-009-9262-y
- Mponela, P., Tamene, L., Ndengu, G., Magreta, R., Kihara, J., and Mango, N. (2016). Determinants of integrated soil fertility management technologies adoption by smallholder farmers in the Chinyanja Triangle of Southern Africa. *Land Use Policy* 59, 38–48. doi: 10.1016/j.landusepol.2016.08.029
- Mtambanengwe, F., and Mapfumo, P. (2005). Organic matter management as an underlying cause for soil fertility gradients on smallholder farms in Zimbabwe. *Nutr. Cycl. Agroecosyst.* 73, 227–243. doi: 10.1007/s10705-005-2652-x
- Mugwe, J., Mugendi, D., Mucheru-Muna, M., Merckx, R., Chianu, J., and Vanlauwe, B. (2009). Determinants of the decision to adopt integrated soil fertility management practices by smallholder farmers in the central highlands of Kenya. *Experi. Agricult.* 45, 61–75. doi: 10.1017/S0014479708007072
- Murphy, R. P., Montes-Molina, J. A., Govaerts, B., Six, J., van Kessel, C., and Fonte, S. J. (2016). Crop residue retention enhances soil properties and nitrogen cycling in smallholder maize systems of Chiapas, Mexico. *Appl. Soil Ecol.* 103, 110–116. doi: 10.1016/j.apsoil.2016.03.014
- Mutuku, E. A., Roobroeck, D., Vanlauwe, B., Boeckx, P., and Cornelis, W. M. (2020). Maize production under combined conservation agriculture and integrated soil fertility management in the sub-humid and semi-arid regions of Kenya. *Field Crops Res.* 254:107833. doi: 10.1016/j.fcr.2020.107833
- Neef, A. (2001). “Land tenure and soil conservation practices-evidence from West Africa and Southeast Asia,” in *Sustaining the Global Farm. Selected Papers from the 10th International Soil Conservation Organization Meeting held May 24–29 at Purdue University and the USDA-ARS-National Soil Erosion Research Laboratory*. Indiana.
- Nekesa, A. O., Okalebo, J. R., and Kimetto, J. R. (2007). “Adoption of Leguminous Trees/Shrubs, Compost and Farmyard Manure (FYM) as alternatives to improving soil fertility in Trans Nzoia District-Kenya,” in *Advances in Integrated Soil Fertility Management in sub-Saharan Africa: Challenges and Opportunities*, eds A. Bationo, B. Waswa, J. Kihara, and J. Kimetu (Dordrecht: Springer). doi: 10.1007/978-1-4020-5760-1\_92
- Nennich, T. D., Harrison, J. H., Vanwieringen, L. M., Meyer, D., Heinrichs, A. J., Weiss, W. P., et al. (2005). Prediction of manure and nutrient excretion from dairy cattle. *J. Dairy Sci.* 88, 3721–3733. doi: 10.3168/jds.S0022-0302(05)73058-7
- Nganga, W. B., Ng’etich, K. O., Macharia, M. J., Kiboi, N. M., Adamtey, N., and Ngetich, K. F. (2020). Multi-influencing-factors’ evaluation for organic-based soil fertility technologies out-scaling in Upper Tana Catchment in Kenya. *Sci. Afri.* 7:e00231. doi: 10.1016/j.sciaf.2019.e00231
- Oduor, F. O., Boedecker, J., Kennedy, G., and Termote, C. (2019). Exploring agrobiodiversity for nutrition: Household on-farm agrobiodiversity is associated with improved quality of diet of young children in Vihiga, Kenya. *PLoS ONE* 14:219680. doi: 10.1371/journal.pone.0219680
- Ojiem, J. O., De Ridder, N., Vanlauwe, B., and Giller, K. E. (2006). Socio-ecological niche: a conceptual framework for integration of legumes in smallholder farming systems. *Int. J. Agric. Sustainab.* 4, 79–93. doi: 10.1080/14735903.2006.9686011
- Ojiem, J. O., Franke, A. C., Vanlauwe, B., De Ridder, N., and Giller, K. E. (2014). Benefits of legume-maize rotations: Assessing the impact of diversity on the productivity of smallholders in Western Kenya. *Field Crops Res.* 168, 75–85. doi: 10.1016/j.fcr.2014.08.004
- Okalebo, J. R., Gathua, K. W., and Woome, P. L. (2002). *Laboratory Methods of Soil and Plant Analysis: A Working Manual*. 2nd edn. (Nairobi: Sacred Africa), 21.
- Palm, C. A., Myers, R. J., and Nandwa, S. M. (1997). Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. *Replenish. Soil Fertil. Afr.* 51, 193–217. doi: 10.2136/sssaspecpub51.c8
- Pedzisa, T., Rugube, L., Winter-Nelson, A., Baylis, K., and Mazvimavi, K. (2015). The intensity of adoption of conservation agriculture by smallholder farmers in Zimbabwe. *Agrekon* 54, 1–22. doi: 10.1080/03031853.2015.1084939
- R Core Team (2019). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. Vienna.
- Rodriguez, D., de Voil, P., Rufino, M. C., Odendo, M., and Van Wijk, M. T. (2017). To mulch or to munch? Big modelling of big data. *Agricult. Syst.* 153, 32–42. doi: 10.1016/j.agsy.2017.01.010
- Rohli, R. V., Andrew Joyner, T., Reynolds, S. J., Shaw, C., and Vázquez, J. R. (2015). Globally extended Köppen-Geiger climate classification and

- temporal shifts in terrestrial climatic types. *Phys. Geogr.* 36, 142–157. doi: 10.1080/02723646.2015.1016382
- Rufino, M. C., Tittonell, P., Van Wijk, M. T., Castellanos-Navarrete, A., Delve, R. J., De Ridder, N., et al. (2007). Manure as a key resource within smallholder farming systems: analysing farm-scale nutrient cycling efficiencies with the NUANCES framework. *Livest. Sci.* 112, 273–287. doi: 10.1016/j.livsci.2007.09.011
- Rusinamhodzi, L., Dahlin, S., and Corbeels, M. (2016). Living within their means: Reallocation of farm resources can help smallholder farmers improve crop yields and soil fertility. *Agric. Ecosyst. Environ.*, 216, 125–136. doi: 10.1016/j.agee.2015.09.033
- Salasya, B., and Stoorvogel, J. (2010). Fuzzy classification for farm household characterization. *Outlook on Agric.* 39, 57–63. doi: 10.5367/000000010791169961
- Sanchez, P. A. (2019). *Properties and Management of Soils in the Tropics*. Cambridge University Press.
- Sawada, Y., Nakata, H., and Tanaka, M. (2019). Short and long recall errors in retrospective household surveys: evidence from a developing country. *J. Dev. Stud.*, 55, 2232–2253. doi: 10.1080/00220388.2018.1539478
- Sheahan, M., and Barrett, C. B. (2017). Ten striking facts about agricultural input use in Sub-Saharan Africa. *Food Policy* 67, 12–25. doi: 10.1016/j.foodpol.2016.09.010
- Smith, A., Snapp, S., Dimes, J., Gwenambira, C., and Chikowo, R. (2016). Doubled-up legume rotations improve soil fertility and maintain productivity under variable conditions in maize-based cropping systems in Malawi. *Agric. Syst.* 145, 139–149. doi: 10.1016/j.agsy.2016.03.008
- Snapp, S. S., Cox, C. M., and Peter, B. G. (2019). Multipurpose legumes for smallholders in sub-Saharan Africa: identification of promising 'scale out' options. *Global Food Security* 23, 22–32. doi: 10.1016/j.gfs.2019.03.002
- Sorre, B. M. (2017). Economic parameters influencing farming activities among households in busia county, Kenya. *Res. J. Human. Cult. Stud.* 3, 26–32. Available online at: Economic Parameters.pdf (iiardpub.org).
- Takahashi, K., Muraoka, R., and Otsuka, K. (2020). Technology adoption, impact, and extension in developing countries' agriculture: A review of the recent literature. *Agric. Econ.* 51, 31–45. doi: 10.1111/agec.12539
- Tittonell, P., and Giller, K. E. (2013). When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. *Field Crops Res.* 143, 76–90. doi: 10.1016/j.fcr.2012.10.007
- Tittonell, P., Van Wijk, M. T., Herrero, M., Rufino, M. C., de Ridder, N., and Giller, K. E. (2009). Beyond resource constraints-Exploring the biophysical feasibility of options for the intensification of smallholder crop-livestock systems in Vihiga district, Kenya. *Agric. Syst.* 101, 1–19. doi: 10.1016/j.agsy.2009.02.003
- Tittonell, P., Vanlauwe, B., Leffelaar, P. A., Shepherd, K. D., and Giller, K. E. (2005). Exploring diversity in soil fertility management of smallholder farms in western Kenya: II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. *Agricult. Ecosyst. Environ.* 110, 166–184. doi: 10.1016/j.agee.2005.04.003
- Turmel, M. S., Speratti, A., Baudron, F., Verhulst, N., and Govaerts, B. (2015). Crop residue management and soil health: A systems analysis. *Agric. Syst.* 134, 6–16. doi: 10.1016/j.agsy.2014.05.009
- Valbuena, D., Erenstein, O., Tui, S. H. K., Abdoulaye, T., Claessens, L., Duncan, A. J., et al. (2012). Conservation Agriculture in mixed crop-livestock systems: Scoping crop residue trade-offs in Sub-Saharan Africa and South Asia. *Field Crops Res.* 132, 175–184. doi: 10.1016/j.fcr.2012.02.022
- Vanlauwe, B., Hungria, M., Kanampiu, F., and Giller, K. E. (2019). The role of legumes in the sustainable intensification of African smallholder agriculture: lessons learnt and challenges for the future. *Agric. Ecosyst. Environ.* 284:106583. doi: 10.1016/j.agee.2019.106583
- Vanlauwe, B., Kihara, J., Chivenge, P., Pypers, P., Coe, R., and Six, J. (2011). Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. *Plant Soil* 339, 35–50. doi: 10.1007/s11104-010-0462-7
- Vanlauwe, B., Tittonell, P., and Mukalama, J. (2007). "Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya," in *Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities*, eds A. Bationo, B. Waswa, J. Kihara, and J. Kimetu (Dordrecht: Springer). doi: 10.1007/978-1-4020-5760-1\_10
- Webb, N. P., Stokes, C. J., and Marshall, N. A. (2013). Integrating biophysical and socio-economic evaluations to improve the efficacy of adaptation assessments for agriculture. *Global Environ. Change* 23, 1164–1177. doi: 10.1016/j.gloenvcha.2013.04.007
- Williams, C. M., Barker, J. C., Sims, J. T. (1999). "Management and utilization of poultry wastes," in *Reviews of Environmental Contamination and Toxicology. Reviews of Environmental Contamination and Toxicology*, ed G. W. Ware (New York, NY: Springer). doi: 10.1007/978-1-4612-1528-8\_3
- Wollburg, P. R., Tiberti, M., and Zezza, A. (2020). *Recall Length and Measurement Error in Agricultural Surveys*. World Bank Policy Research Working Paper. doi: 10.1016/j.foodpol.2020.102003
- Wood, S. A., Tirfessa, D., and Baudron, F. (2018). Soil organic matter underlies crop nutritional quality and productivity in smallholder agriculture. *Agric. Ecosyst. Environ.* 266, 100–108. doi: 10.1016/j.agee.2018.07.025
- Zingore, S., Murwira, H. K., Delve, R. J., and Giller, K. E. (2007). Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. *Agric. Ecosyst. Environ.* 119, 112–126. doi: 10.1016/j.agee.2006.06.019
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