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On-farm trial assessing combined organic and mineral fertilizer amendments on vegetable yields in central Uganda

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ABSTRACT

Integrated Soil Fertility Management (ISFM) is a soil management approach that emphasizes combined application of organic and mineral fertilizer inputs with the goal of improving yields and fertilizer use efficiency. Combined applications have resulted in a positive interaction between organic inputs and mineral fertilizers on vegetable yields, where yields from combined treatments are greater than yields from sole fertilizer treatments. ISFM studies have been conducted with a diverse range of crops, including grains, legumes, tubers, and bananas, but not vegetable crops. Particularly lacking are ISFM studies conducted under participatory, smallholder farmer management. A researcher-designed, farmer-managed, on-farm study was conducted on highly weathered soils (Ferralsols) in the Lake Victoria Crescent of Uganda to determine the influence of combined organic and mineral fertilizer treatments on yields of a commonly grown indigenous leafy vegetable known as nakati (*Solanum aethiopicum*). Farmer-managed plots allowed for the effect of farmer participation and management to be analyzed in conjunction with fertilizer treatment effects. A gradient of 100% organic (sole manure) to 0% organic (sole mineral) fertilizer treatments were applied at both an upper (200 kg ha^{-1}) and lower (100 kg ha^{-1}) nitrogen (N) rate. N rates were derived from survey results on typical organic application rates used by smallholder farmers in their vegetable plots. Fertilizer treatments resulted in significantly different vegetable yields; however, combined treatments did not necessarily result in higher yields than sole treatments. Differences between organic-mineral ratios were only seen when fertilizers were applied at the higher N rate. The highest yields were obtained when fertilizer was applied at a ratio of 67% organic to 33% mineral fertilizer. Effects of soil properties on yield were also observed; after accounting for the effect of fertilizer treatment, yields significantly increased with increasing soil pH. Farmer participation level had a significant effect on yield. All treatment means were significantly increased by greater participation in the study, and the interactive effects of all treatments became less negative when participation was higher. On-farm studies are needed to demonstrate the applicability of a technology under real world conditions, but trials need to maintain farmers' interest throughout the study period.

1. Introduction

Decline in soil fertility is considered by many to be the most important constraint to crop production across sub-Saharan Africa (Sanchez, 2002). Tropical soils are inherently susceptible to nutrient loss, but poor agricultural management further exacerbates the rate at which nutrients are lost. Nutrient mining occurs as a result of continuous nutrient removal through crop harvest without nutrient replenishment, uncontrolled soil erosion, and burning of crop residues rather than the return of organic resources to the soil. Soil fertility is declining faster in Uganda than in other countries of sub-Saharan Africa, yet smallholder farmers have limited adoption of soil fertility management technologies developed by researchers (Esilaba et al., 2005; Nkonya et al., 2005).

Researchers have long advocated for a soil fertility management approach that combines mineral fertilizer with organic inputs because adequate quantities of either fertilizer source on their own are often unavailable or unaffordable to smallholder farmers (Bationo et al., 1998). Manure is frequently of low or imbalanced nutrient content, which means manure sources are less likely to meet crop demands and can lead to temporary nutrient

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immobilization following application (Mafongoya et al., 2006; Masaka et al., 2013; Vanlauwe et al., 2005). Mineral fertilizers can supplement the nutrient supply of organic inputs and are thought to be necessary to correct nutrient outflows from smallholder fields (Nkonya et al., 2005; Tittonell et al., 2008a). Integrated Soil Fertility Management (ISFM) emphasizes combining both input types with the recognition that adequate quantities of either input on its own are often unavailable or unaffordable for smallholder farmers. A meta-analysis of studies demonstrated that, across sub-Saharan Africa, the combined use of organic inputs and nitrogen fertilizers leads to a greater yield response than either input on its own (Chivenge et al., 2010). Some trials have also reported a positive "interactive effect," or a boost in crop yields beyond what is observed when either amendment is applied alone at a nutrient rate equivalent to the combination (Bekunda et al., 2010). This interactive effect is thought to occur through two mechanisms. First, organic inputs may temporarily immobilize mineral nitrogen (N) from fertilizer and prevent the rapid leaching of N that is often witnessed in tropical systems (Vanlauwe et al., 2002). Second, yield increases may occur indirectly as general soil conditions are improved through the addition of organic inputs (Vanlauwe et al., 2001a). Both mechanisms most likely occur simultaneously and increase use efficiency of mineral fertilizers (Mosier et al., 2004).

Despite research trials demonstrating yield benefits from combined nutrient sources, ISFM adoption in central Uganda is currently low due to the lack of recommendations appropriate for highly weathered soils undergoing rapid nutrient mining. The Lake Victoria Basin is dominated by Ferralsols, which are characterized by low soil pH, low nutrient reserves and availability, and high clay content. Ferralsols are the most dominant (25%) soil type in Uganda, and an additional quarter of Uganda's soil types are also considered highly weathered (Bamutaze, 2015). Rapid population growth in the Lake Victoria Basin is accelerating the rates of soil nutrient mining on these already nutrient-poor soils. Understanding how highly weathered soil types respond to combined fertilizer treatments can potentially increase the adoption of ISFM soil management among smallholder farmers.

It is known that on-station research results often do not accurately reflect yield outcomes when technologies are moved onto surrounding farms (Leeuwis, 2004). Yield responses to mineral fertilizer use are often significantly lower and more variable under typical smallholder conditions than yield responses seen on research stations (Sileshi et al., 2010). Mugwe et al. (2008) found that on-farm yields of combined organic and mineral N treatments were generally >50% lower than the same treatment plots located on-station in western Kenya. Lower yield outcomes on farms are thought to result in part from less consistent crop management by farmers in the form of less timely planting, weeding, and watering. Trials that are designed by researchers, but managed by farmers, can produce reliable biophysical data over a broad range of management approaches (Franzel and Coe, 2002; Selener, 1997). Participatory trials ensure that research results accurately incorporate the effects of farmer management, which could otherwise obscure treatment effects when technologies move onto farms (Mutsaers et al., 1997). Technologies that perform well during on-farm trials are most likely particularly adept at eliciting a yield response under a variety of conditions.

Our objectives were to measure the effect of organic and mineral fertilizers, separately and combined, on indigenous vegetable yields through an on-farm, researcher-designed, farmer-managed trial in the Lake Victoria Crescent of Uganda. We hypothesized that mineral fertilizer would complement the organic resources already used by smallholders farming on highly weathered clay Ferralsols. The use of combined fertilizer treatments was expected to lead to yield gains beyond what either input generates alone, resulting in a positive interactive effect under on-farm conditions.

2. Materials and methods

2.1. Study site

The study plots are located within central Uganda's Lake Victoria Crescent region around the Nkokonjeru town council (0°14′58″ N; 32°54′ 39″ E). The region is sub-humid tropic and has two distinct rainfall periods, allowing for two cropping seasons per year. On average, the region receives approximately 1500 mm of rainfall distributed with bimodal peaks in April and November. Temperature ranges from 17 to 27 °C with a daily mean of 22 °C. This region is characterized by highly weathered, clay texture soils classified as orthic Ferralsols (FAO, 1977). Historically, the region was highland tropical forest, but over the past twenty years has been converted to primarily mixed banana/coffee systems with maize, beans, cassava, and potatoes as other important staple crops. Smallholder farms are typically less than one hectare in area.

2.2. Study crop

The indigenous vegetable *Solanum aethiopicum*, locally referred to as nakati, was chosen as a test crop because of its commercial and nutritional importance in central Uganda (Ssekabembe, 2003). Nakati can be grown as a bushy perennial or annual. Unlike the related *Solanum aethiopicum* 'Gilo group' whose white or cream colored fruits are harvested and referred to as African eggplants, the leaves and stems of *Solanum aethiopicum* 'Shum group' are not hairy and are used as a vegetable (Shackleton et al., 2009). The small red fruits of the 'Shum group' plants are not eaten. Nakati can be present on farms as a weedy species, but it is more often deliberately cultivated for sale or household use. Farmers value nakati for its relatively high and stable market price, as well as the fact that it is capable of surviving and re-growing after prolonged droughts (Ssekabembe, 2003). Nakati is frequently found in Kampala markets. It has a large geographic range across Africa and is also grown in South America and the Caribbean (Schippers, 2000).

2.3. Study design

Trials were conducted during two consecutive growing seasons, the short (April) and long (Aug/Sept) rains of 2013. Experimental trials (31 during the short rainy season and 38 during the long rainy season) were established on-farm in a randomized block design, with one replicate per treatment in each block (farm). Forty-five total farms were included in the study; twenty-four plots repeated the experiment both seasons. Plots offered by farmers were accepted if they were free of shade trees, tree stumps, burned areas and other environmental conditions that could create confounding effects. Plots were located within a 50 km radius between 1150 to 1233 m above sea level. Plot slopes ranged from 0 to 14%.

Treatments consisted of a control and varying levels of composted cow manure and mineral fertilizer (urea) to reach two different levels of N application rates. Nitrogen rates were calculated based on survey results capturing farmers' home garden fertilization practices. Farmers provided their application rates in wheelbarrows, which were then translated to a lower rate of 100 kg N ha^{-1} and an upper rate of 200 kg N ha^{-1} by taking the average dry weight and N content of three wheelbarrows of manure. Even though a scarcity of manure supplies would prevent farmers from fertilizing at this rate across a full hectare, the rates used in this study represent the lower and upper range of manure application rates used by farmers in the region on their kitchen vegetable plots. Manure was obtained from a local kraal that collected manure in an open heap to be sold within the community. The manure was minimally mixed with soil, sawdust or plant material. Each season, the manure was thoroughly mixed at a central location, sampled for nutrient content and water weight, and measured and bagged for each treatment before it was brought to farms. The treatments were: (A) control – no added N inputs, (B) 100 kg N ha^{-1} applied as 100% organic, (C) 100 kg N ha^{-1} applied as 67% organic, (D) 100 kg N ha^{-1} as 33% organic, (E) 100 kg N ha^{-1} as 0% organic, (F) 200 kg N ha^{-1} as 100% organic, (G) 200 kg N ha^{-1} as 67% organic, (H) 200 kg N ha^{-1} as 33% organic, and (I) 200 kg N ha^{-1} as 0% organic.

Nine sub-plots of 1 × 1 m each with a half meter buffer were randomized and established at every farm (i.e., block). Nakati seed was obtained from a local seed supplier, mixed and distributed evenly across plots at a rate of 3.75 g/m^2. Due to poor germination during the short rainy season, seeds were re-sown one month after the first planting date. Urea was also reapplied to treatment plots receiving mineral fertilizer to replace nutrients that had leached below 2 cm and out of the range of germinating seeds. Urea was reapplied at a rate of 10 kg N ha^{-1} for treatments receiving less than 100 kg N ha^{-1} from urea and at a rate of 20 kg ha^{-1} for treatments receiving over 100 kg N ha^{-1} from urea. Manure and mineral fertilizer were mixed into plots using a hand hoe to a depth of approximately 15 cm at planting. A one-time application of single super phosphate at a rate of 50 kg P ha^{-1} and 38 kg S ha^{-1} was applied to all plots prior to the short rainy season.

Researchers maintained rain gauges at each village while farmers kept records of the amount of water applied through hand irrigations. These records were later combined to create plot-level water supply records. Crops were harvested when 70% of fields had reached physiological maturity, which was defined as 50% of the plants with flower buds. Crops were harvested from the middle 0.5 m^2 of each treatment subplot. Total aboveground biomass (stems and leaves) was oven dried at 70 °C and then ground and weighed to obtain g dry weight (DW) per m^2, expressed as kg ha^{-1}.

Plots were primarily managed by farmers. Each farmer was given a binary ranking of high or low participation in the trial depending on their management style that season. Each farmer's participation was assessed independently by three field assistants who were the primary liaisons with the farmers. Scores were compared and debated until there was a consensus among field assistants on each farmer's participation level during individual seasons.

2.4. Baseline soil and manure analyses

Soils were sampled as a composite ($n = 5$) from each field to a depth of 15 cm using an auger. Soils were air dried and analyzed by the World Agroforestry Centre (ICRAF) Soil-Plant Spectral Diagnostics Laboratory and the affiliated Crop Nutrient Laboratory Services (ISO 17025 accredited). Soils were analyzed for pH(water), electrical conductivity (EC) and Mehlich 3-extractable Al, P, K, Ca, Mg, Na, S, Fe, Mn, Cu, B, and Zn using atomic emission spectrometry (ICP-OES). Soil particle size fractions were determined by laser diffraction (3000–0.01 mm) using a Horiba particle size analyzer (Model: LA-950V2; Horiba Ltd., Kyoto, Japan). Phosphorus sorption index (PSI) was determined based on the method described by Towett et al. (2015). Briefly, 1.5 g soil were equilibrated in 30 mL of 75 mg P L^{-1} in 0.03 M KCl solution by shaking for 20 h at 25 °C. Following filtration, P was quantified in supernatant. Exchangeable acidity was determined by NaOH titration of 1 M KCl extracts of soils (1:10 mass:volume) (Anderson and Ingram, 1993). Total carbon (C) and nitrogen (N) were analyzed by dry combustion gas chromatography. Soils were additionally analyzed by diffuse reflectance infrared Fourier transform (DRIFT) spectroscopy. Mid-infrared spectra (4000–600 cm^{-1}) were used to confirm mineralogical similarity of soils (kaolinite, quartz, and iron oxides) and investigate potential differences in SOM composition among plots (Supporting Information).

A composite manure sample was analyzed at Makerere University in Kampala for moisture content, total N, and Mehlich 3-extractable P and K. Manure nutrient and water content varied from short rainy season (0.88% N; 0.45% P; 2.56% K; 11.1% OC; and 45% water) to long rainy season (0.61% N; 0.21% P; 0.16% K; 10.5% OC; and 48% water), thus varying the amount of manure applied each season. The manure C/N ratio increased from 12.6 in the short rainy season to 17 in the long rainy season. Manure was applied at the following rates during the short and long rainy seasons, respectively: 100N_allOrg: 11,363 and 16,393 kg ha^{-1}; 100N_66% Org: 7613 and 10,984 kg ha^{-1}; 100N_33% Org: 3750 and 5410 kg ha^{-1}; 100N_noOrg: 0 and 0 kg ha^{-1}; 200N_allOrg: 22,727 and 32,787 kg ha^{-1}; 200N_67% Org: 15,147 and 21,852 kg ha^{-1}; 200N_33% Org: 7568 and 10,918 kg ha^{-1}; 200N_noOrg: 0 and 0 kg ha^{-1}.

2.5. Statistical analysis

Fertilizer treatment effects on yield, measured as aboveground biomass, were analyzed through a mixed-effects analysis of variance (ANOVA) using the nlme package in R Version 2.1.15. Treatment, season, and farmer participation level were included in the model as fixed effects and tested for their interaction. Farms were considered a random effect to broaden the conclusions to the general region. Graphical analysis of residuals was employed to test for normality and constant variance. To correct for a non-normal distribution, yield values were transformed through a square root transformation and then winsorized, a process that replaced 10% of yield values with values equal to those at the 95% and 5% percentiles of the error distribution. Significant differences between means were determined using a Tukey's post-hoc honest significant difference (HSD) analysis and the lsmeans package with $p < 0.05$ (Lenth and Herva, 2014).

A positive interactive effect signifies the additional yield obtained through the combined application of organic inputs and mineral fertilizers compared with what is obtained when either input is applied on its own at the same total rate in the combined application. The potential interactive effects on yield was calculated according to Vanlauwe et al. (2001):

$$\text{Interactive effects} = Y_{\text{comb}} - Y_{\text{control}} - (Y_{\text{manure}} - Y_{\text{control}}) - (Y_{\text{Nfert}} - Y_{\text{control}})$$

where Y_{control}, Y_{Nfert}, Y_{manure}, and Y_{comb} are mean yields in the control treatment, sole N fertilizer (100N_allOrg and 200N_allOrg), sole manure (100N_noOrg and 200N_noOrg), and the combined manure and mineral fertilizer treatments, respectively. An accurate interpretation of the interactive effect of combined inputs is only possible if the yield responses to organic or mineral N are linear at all application rates. A one-sample t-test was used to determine if any treatment led to statistically significant positive interactive effects ($IE > 0$) across all farms.

Linear correlation between yield and measured soil properties was determined using Pearson's correlation coefficient. Soil properties with a significant Pearson's correlation coefficient were alternatingly included in a mixed-effects model to test each property's effects on yield. Treatments, participation level, and season were included as fixed effects and farms as random.

3. Results

3.1. Farmer participation yield effects

Fifteen farms in the short rains season and 16 in the long rains season had active farmers with high levels of participation in the trial. Participation had a stronger effect on yield ($F = 36.31$) than treatment or season (Table 2). Across treatments, farmers with high participation secured 55% higher yields than farmers with low participation. Yields from all treatments, even control yields, rose as a result of more attention (Fig. 1). Farmers' interest level in the trial is an important factor influencing the degree to which they invested time in weeding, watering and protecting the research plot from livestock and other intruders. Farmers with high participation levels typically weeded the plot 1–2 times per week, watered the plot every 1-2 days, and protected the plot from household livestock. High participation farmers paid particular attention to the plot during seedling establishment and could discuss details of the crop development, including differences between treatments, when prompted. Farmers with low participation levels did not visit the plot regularly and therefore did not weed, water, or protect the plot until requested by the research team. Farmer participation varied season to season; participation could go up or down after observing crop growth from the preceding season or sudden outside demands on farmer time could influence farmers' ability to participate in the study.

3.2. Seasonal yield effects

Yields varied slightly due to seasonal effects (Table 2). Yields were slightly higher in the short rainy season than the long rainy season ($t = -2.05$, df = 560, $p = 0.0408$), but there were fewer significant differences between treatments. During the short rainy season, only plots with 200 kg N ha^{-1} applied as 67% from manure had significantly higher yields ($p = 0.001$) than control plots according to a pairwise comparison for treatments by season. The long rainy season resulted in every treatment except sole mineral fertilizer treatments having significantly higher yields ($p < 0.02$) than control plots. During the short rainy season, there was more total precipitation in the initial weeks following crop establishment (SI Fig. 1). Even though the long rainy season had greater total precipitation, the majority of the rain fell during the latter stages of nakati growth.

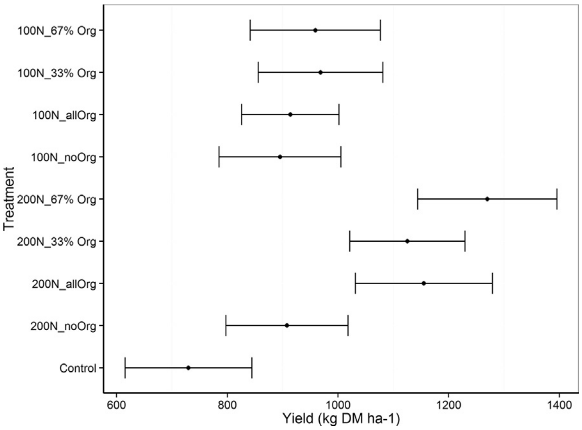

Fig. 2. Mean nakati (*Solanum aethiopicum*) yields for sole organic, sole mineral, and combined fertilizer treatments at two N application rates (100 and 200 kg N ha^{-1}). Error bars depict standard error of the mean.

3.3. Fertilizer treatment yield effects

Even after accounting for significant participation and seasonal effects on yield, fertilizer treatments resulted in significantly different mean yields (Table 2). All treatment means were significantly higher than control means, with the notable exception of sole mineral fertilizer treatments at both N rates (Table 2). On average, 200 kg N ha^{-1} applied as 67% sourced from manure (200N_67% Org) resulted in the highest yields. Applying 200 kg N ha^{-1} as combined fertilizer applications (33 and 67% manure) resulted in significantly higher yields than 200 kg N ha^{-1} applied as sole mineral N (200N_noOrg). Varying the proportion of N sourced from manure however did not result in significant yield differences at either N rate. At lower application rates, there were no yield differences between any organic or mineral fertilizer combinations.

Higher N rates also did not necessarily result in higher yields than lower N rates (Fig. 2). Only one 200 kg N ha^{-1} treatment,

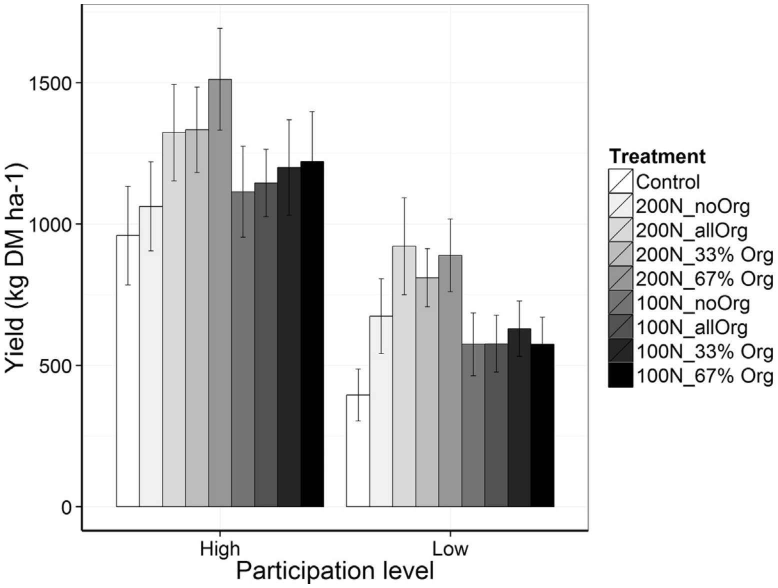

Fig. 1. Mean nakati (*Solanum aethiopicum*) yields for sole organic, sole mineral, and combined fertilizer treatments at two N application rates (100 and 200 kg N ha^{-1}) by farmer participation level. Error bars depict standard error of mean.

200N_ 67% Org, had significantly higher yields than all 100 kg N ha^{-1} treatments. Nakati dry weight yields under 200 kg N ha^{-1} applied as 33% and 100% manure were significantly higher than yields under 100 kg N ha^{-1} applied as sole mineral fertilizer, but not other 100 kg N ha^{-1} treatments. A pairwise comparision of organic-mineral ratios across N application rates shows that only when 67% of N is sourced from manure are there significantly higher yields from a higher N application rate ($p = 0.0048$). Applying manure to provide N at 0% ($p = 1$), 33% ($p = 0.3752$), or 100% ($p = 0.6009$) did not result in higher yields at higher N rates.

When farmer participation was high, yields from combined (33 and 67%) and sole organic fertilizer (100%) applied at both 200 kg N ha^{-1} and 100 kg N ha^{-1} were significantly different than control yields ($p < 0.05$). In contrast, when farmer participation was low, only yields from combined (33 and 67%) and sole organic fertilizer (100%) applied at 200 kg N ha^{-1} were significantly different than control yields ($p < 0.01$). There were no treatments significantly different than control when N was applied at 100 kg N ha^{-1}.

3.4. Treatment interactions with soil properties

Soil analyses showed substantial variability in many chemical properties across farms (Table 1). Nakati yield was strongly ($p < 0.05$) correlated with initial soil pH, EC, and Mehlich 3-extractable P, K, Ca, Mg and B (Table 3). Soil pH, K, EC, Al, and PSI also had a significant effect on yield distinguishable from the treatment effect. Nakati yields responded most to changes in soil pH; yield increased by 161 kg ha^{-1} for every one unit increase in pH ($t = 4.63$, df = 43, $p < 0.0001$). Extractable K and EC were the only measured soil properties that had a significant interaction with fertilizer treatments.

3.5. Interactive effects between manure and mineral nitrogen fertilizer

The interactive yield effect was calculated to determine if combining inputs resulted in a synergistic effect, or yield gains that are greater than the sum of what is seen when applying organic inputs and mineral fertilizer separately and at the same rate. A one-sample *t*-test showed that no combined fertilizer treatment led to a positive interactive effect across all sites (Table 4). Although the mean interactive effect was found to be negative across all ratios and N rates, it was substantially less negative at the higher N rate of 200 kg ha^{-1} applied as 67% organic. High farmer participation also resulted in less negative interactive effects for all ratios and N rates (Fig. 3). When farmer participation was high, plots with 200 kg N ha^{-1} applied as 67% manure had a mean positive interactive effect, although the interactive effect was still not statistically greater than zero (t (38) = 0.5942, p = 0.2779).

Table 1
Initial surface soil (0–15 cm) chemical and physical properties of 45 farms in Buikwe and Mukono Districts, Uganda.[a]

	Mean	Standard deviation
Clay (%)	75	10
Silt (%)	13	4
Sand (%)	11	7
Total Nitrogen (%)	0.17	0.05
Extractable P (μg/g)	22	39
Extractable K (μg/g)	209	238
Total Carbon (%)	2.1	0.6
C/N ratio	12.0	1
Aluminum (μg/g)	1071	163
Magnesium (μg/g)	700	282
Calcium (μg/g)	1277	532
Boron (μg/g)	0.24	0.32
EC (μS/cm)	103.2	53
PSI (meq/100 g)	83.7	29
pH (water)	5.6	0.6

[a] Samples were bulked into one composite sample per farm.

Table 2
ANOVA and post-hoc test results of trial applying combined versus sole fertilizer inputs to nakati (*Solanum aethiopicum*) on 45 farms in the Lake Victoria Crescent of Uganda in 2013. Treatments varied ratio of N sourced from manure or N fertilizer applied at either 100 or 200 kg N ha^{-1}. ANOVA model tested treatments, participation level, and season as fixed effects and farm site as a random effect.

Sources of variability	DF[a]	*F* value	*p* > *F*
Treatment	8, 560	9.80	<0.0001
Participation level	1, 560	36.31	<0.0001
Season	1, 560	4.20	0.0408

Treatment	LS Means[b] (kg ha^{-1})	SE	Tukey Group
Control	21	1.64	a
200_noOrg	25	1.65	ab
100_noOrg	26	1.64	abc
100_67% Org	27	1.64	bcd
100_33% Org	27	1.64	bcd
100_allOrg	27	1.64	bcd
200_allOrg	30	1.65	cde
200_33% Org	31	1.65	de
200_67% Org	32	1.65	e

[a] DF = numerator and denominator degrees of freedom.

[b] Results are averaged over levels of participation and season and transformed through a square root transformation to obtain least squared means. Confidence level of 0.95 and alpha = 0.05.

4. Discussion

Combining organic inputs and mineral fertilizers has shown positive yield results in research stations across sub-Saharan African agro-ecosystems; however, there is a need to understand on-farm constraints to this technology in order to maximize technology uptake and minimize risks to farmers (Paul et al., 2014). Weed and water management had a significant impact on crop response to all fertilizer treatments, including combined fertilizer treatments. When farmers did not weed or water their plots, yield responses to all fertilizer treatments were significantly diminished. Even after accounting for farmer management, combining organic inputs and mineral fertilizers did not necessarily result in higher yields than sole organic inputs on acidic, weathered soils in the Lake Victoria Crescent. These results agree with the observations of Mucheru-Muna et al. (2013) that maize grown with sole organic inputs outperformed maize grown with combined organic and mineral fertilizers in low fertility Nitisols in Kenya. In addition, we saw that nakati showed a significant response to organic inputs, but not sole mineral N applications. Nakati yields were significantly lower in sole mineral N plots than combined or sole organic plots, demonstrating the risks farmers face when applying sole mineral fertilizer to degraded Ferralsols (Sileshi et al., 2010).

4.1. On-farm fertilizer trials require good agricultural practices

Good agricultural practices help ensure efficient utilization of added nutrients. Farmers' timeliness in weeding, watering and protecting the plot from livestock had a significant effect on nakati's response to fertilizer. Nakati plots that received timely management had an agronomic efficiency of 2.8 kg DM kg N^{-1} versus 2.6 for plots without timely management. In western Kenya, fertilized maize plots under farmers' management yielded less than non-fertilized, researcher-managed control plots placed on the same plots the following season (Tittonell et al., 2008b). They concluded that a range of improved agronomic practices – beyond fertility management – were required to harness the benefits of

Table 3
Select soil variables with significant correlation or effect on nakati (*Solanum aethiopicum*) yield (km DM ha^{-1}) beyond the treatment effect. Soil variables with significant treatment interaction also shown. Treatments varied ratio of N sourced from manure or N fertilizer applied at either 100 or 200 kg N ha^{-1} on 45 farms in the Lake Victoria Crescent of Uganda in 2013. In all cases, treatment, participation level and season remained significant ($p < 0.05$, not shown).

Source of variation	Correlation coefficient (r)	p value	DF	F value	p value
pH (water)	0.46	0.0209	1, 43	19.7973	0.0001***
Trt × pH			8, 552	1.1386	0.3353
Extractable K (μg/g)	0.67	0.0002	1, 43	27.1928	<0.0001***
Trt × K			8, 552	2.6853	0.0067***
EC (μS/cm)	0.56	0.0037	1, 43	5.8597	0.0198*
Trt × EC			8, 552	3.7215	0.0003***
Al (μg/g)	−0.20	<0.0001	1, 43	9.4507	0.0037**
Trt × Al			8, 552	1.3239	0.2287
PSI (meq/100 g)	−0.20	<0.0001	1, 43	7.9904	0.0071**
Trt × PSI			8, 552	2.1589	0.0291*
Extractable P (μg/g)	0.43	0.0335			
Ca (μg/g)	0.40	0.0471			
Mg (μg/g)	0.47	0.0191			
B (μg/g)	0.40	0.0459			

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

Table 4
Results of one sample *t*-test, $H_a > 0$, assessing the interactive effect of applying combined versus sole fertilizer inputs to nakati (*Solanum aethiopicum*) on 45 farms in the Lake Victoria Crescent of Uganda in 2013. Treatments varied ratio of N sourced from manure or N fertilizer applied at either 100 or 200 kg N ha^{-1}.

Treatment	Mean interactive effect	Standard deviation	t value	DF	p value
Lo-33% Org	−110.8	878.0	−1.05	68	0.8509
Lo-67% Org	−120.3	982.2	−1.02	68	0.8437
Hi-33% Org	−223.6	1241.5	−1.45	64	0.9243
Hi-67% Org	−6.5	1174.8	−0.04	64	0.5178

mineral fertilizer applications. Even in this trial, unfertilized nakati yields were higher where farmers practiced timely management. Researchers in Malawi demonstrated that the economic returns of a single early weeding in maize production can be equivalent to the returns seen from one bag of ammonium nitrate (Dimes et al., 2002). Although it is well understood that good agronomic practices are essential for the efficient use of fertilizer, it is not always possible for farmers to employ them.

On-farm trials are an opportunity to understand yield responses to fertilizer applications under real world conditions (Defoer et al., 2000; van de Fliert and Braun, 2002; Veldhuizen et al., 1997). Although the large number of uncontrolled

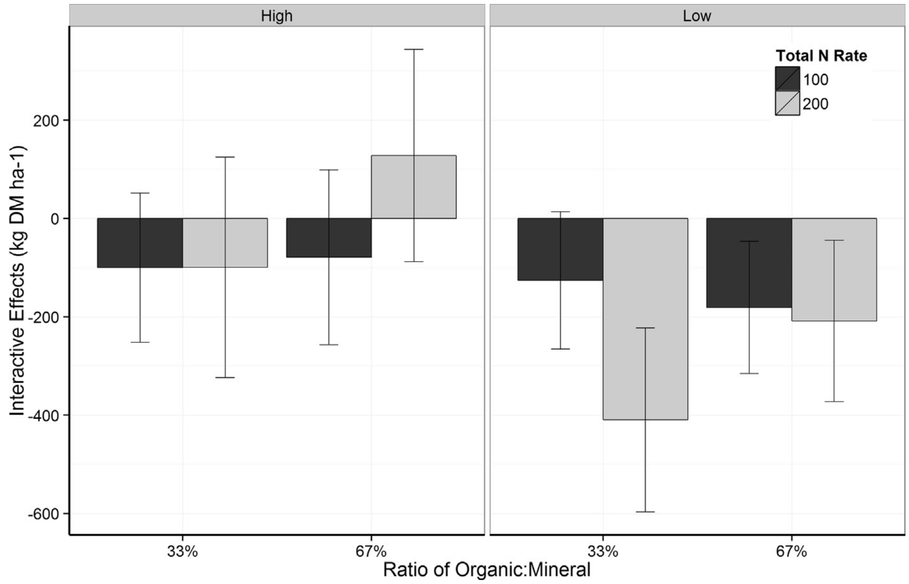

Fig. 3. Interactive effect of combining organic and mineral fertilizer at two ratios (33 and 66% N sourced from organic) and two N application rates on nakati (*Solanum aethiopicum*) yields at high and low levels of farmer participation. Black bars indicate treatments with 200 kg N ha^{-1} applied and grey indicate 100 kg N ha^{-1}. Error bars depict standard error of the mean.

management factors present in on-farm studies make it more difficult to isolate treatment effects, on-farm trials are effective at testing the robustness of a technology before it is disseminated to farmers (Franzel and Coe, 2002). Successful on-farm trials require practitioners to understand the difference between their objectives and farmers' objectives when entering into a research partnership (van Asten et al., 2009). Bentley (1994) articulated that smallholder farmers are typically not concerned in the same way as scientists with whether research results can be replicated, extrapolated or generalized and may therefore modify their management strategy during the trial to suit their objectives at the moment. During discussions with farmers, we found that some dedicated farmers were maximizing their yield from the study plot by selectively watering and weeding only the higher-yielding treatment sub-plots while ignoring slower growing treatments. Other farmers were intent on pleasing the researchers by presenting a uniform study plot and weeding out the "extra" nakati before field visits. Bridging farmers' and scientists' different perspectives and objectives requires discussion prior to the trial to identify potentially divergent short and long-term objectives and expectations of each stakeholder.

Researchers can also improve the effectiveness of farmer participatory research by carefully introducing the study and its requirements to farmers, including an estimate of the expected labor involved. Household surveys conducted with nakati farmers in the Nkokonjeru region showed that weeding consumes the greatest proportion of time farmers spent at their nakati plot; on average, weeding required 20 min m^{-2}. Researchers who work with farmers must find a way of rewarding farmers' time investment appropriately, recognizing that farmers value both immediate, in-season rewards and the longer-term reward of new knowledge and skills. Both may be required to maintain farmer interest at points when labor demands are at their highest. Designing trials from the onset as multi-season studies with a fluctuating number of study participants per season will allow farmers to enter and exit the study as their interest dictates. This may mean designing research studies capable of analyzing an unpredictable number of plots if farmers withdraw land or researchers identify other interested and reliable farmer partners.

We found it was not possible to predict which farmers would be active participants and reliable research partners; well-tended plots were spread among male and female farmers, and wealthy and poor households. This was a strong benefit of not relying on farmers already favored by local extension personnel. A broad range of farmer partners offered more opportunities to test the technology under varying socio-agro-ecological conditions. The approach also resulted in new "early adopter" farmers who were impressed with the research findings on their plots and became informal community resources disseminating information about the technology within their community. Building mutually beneficial relationships between farmers and researchers takes significant time, but is ultimately necessary to shift away from top-down research towards co-designed agricultural solutions.

4.2. Combined treatments did not boost vegetable yields

When management effects were included, combined fertilizer treatments did not necessarily result in higher yields than organic inputs alone. A meta-analysis comparing yield differences between combined and sole fertilizer treatments on clayey and sandy textured soils identified fewer differences between treatments on clayey soils relative to the sandy soil (Chivenge et al., 2010). There are conflicting reasons for the lower crop response to mineral fertilizer on clayey soils. For instance, higher application rates of combined manure and mineral N fertilizer on clayey soils in Zimbabwe and Kenya resulted in no additional yield gains presumably because N was no longer a limiting factor (Chivenge et al., 2009; Mtambanengwe et al., 2006). Nakati N uptake is estimated to be approximately 29 kg N ha^{-1}, given an average rate of 4% N per kg dry biomass and average yield of 730 kg dry biomass ha^{-1}, far below even the lower rate of 100 kg N ha^{-1} applied. Alternatively, it is possible that mineral N leached below the root zone and was not readily available to the crop. Large amounts of NO_3^- (27–37 kg N ha^{-1} m^{-1}) have been found at 0.5–4 m depth after continuous maize cultivation on acid soils in the subhumid highlands of Kenya (Shepherd et al., 2000). Acid soils of the tropics have been shown to sorb NO^-_3 in subsurface layers despite heavy tropical storms due to positively charged sites on kaolinitic and allophanic materials, and protonated hydroxyl groups of aluminum and iron oxides (Cahn et al., 1992; Wong et al., 1990). It is also possible that the soils were non-responsive to N fertilizers because of other nutrient deficiencies that prevented crop growth (Zingore et al., 2007).

Although positive interactive effects were not seen in this study, there was a trend towards positive yield effects when management was good and high amounts of organic inputs were used with small additions of mineral N (200N_67% Org). Positive interactive effects are in part attributable to temporary immobilization of N early in the season so that N is protected from leaching and available for later crop uptake. In studies on maize production using combined inputs on clayey soils, low quality organic material, such as maize stover or sawdust, produced a positive interactive effect whereas high quality organic material, such as tithonia, did not (Gentile et al., 2010). The high quality organic resources used most likely did not release immobilized N in synchrony with maize uptake, as high quality materials have been shown to decompose and release N quickly in clayey soils (Gentile et al., 2008). While temporary N immobilization is desired for maize production, short duration vegetable crops require rapid N mineralization and thus might need very different conditions to attain a positive interactive effect. Manure produced on smallholder farms is often of low quality and can lead to N immobilization directly following incorporation (Nyamangara et al., 1999). High quality manure is more likely to produce a positive interactive effect in vegetable crops than low quality manure.

4.3. Multiple benefits of applying organic inputs to highly weathered soils

4.3.1. Labile C

We found that crop yields increased through the addition of organic inputs despite the high clay and total C content of the soils. For highly weathered soils with 1:1 clays of low CEC, organic amendments might be needed to supply labile soil C capable of increasing microbial N and P turnover. Organic amendments significantly increased the labile C fractions of a Ferralsol in western Kenya after two seasons (Ngome et al., 2011). The four-fold SOM gradient represented by the study sites (1.1–4.2% C) did not entail a non-linear shift in a spectroscopic index of humification associated with SOM lability (Margenot et al., 2015), suggesting similarity of SOM lability across sites (SI Figs. 2–5).

4.3.2. Multi-nutrient soil deficiencies

Organic amendments also may have increased yields due to the addition of nutrients other than N. Baseline soil K and yield were highly correlated ($r = 0.67$, $p = 0.0002$), pointing to potential K deficiencies as a factor in yield loss. In the studied district and in other banana-growing regions of Uganda, partial nutrient balance calculations revealed substantial K export through removal of banana fruit and residue, resulting in proportionally greater removal of K than of N and P from the soils (Esilaba et al., 2005). Soils sampled from 1999 to 2002 from 62 sites across

Uganda showed that K was often below critical concentrations for most crops (Ssali, 2002). A traditional practice is to grow nakati in plots where crop residue or rubbish has previously been burned. The resulting ash contains high levels of K, and therefore the farmers' preference to grow this vegetable on burned areas may be indicative of the crop's high K requirements and/or a K deficiency in the soil.

Microbial biomass P could be another important plant-available P source that is increased through additions of organic material. Maize yields have been shown to be strongly associated with microbial biomass P in highly weathered, P-deficient tropical soils like the ones in this study (Ayaga et al., 2006). Koutika et al. (2013) demonstrated that additions of manure with inorganic P fertilizer increased P microbial biomass in highly P fixing soil, however this effect was not seen in low P fixing soil with higher organic matter concentrations (2.47% C) and low pH (5.3).

4.3.3. Soil pH

Soil pH had a significant effect on yield. Although this study did not measure post-application soil pH, numerous studies have shown that manure applications increase the pH of acidic soils within a single season and with continued, long-term applications (Bado et al., 2004; Bedada et al., 2014; Haynes and Mokolobate, 2001; Whalen et al., 2000). Increases in soil pH following manure application in acidic, weathered soils likely reflect the addition of base cations (Mg^{2+}, Ca^{2+}), which decrease exchangeable acidity (de Ridder and van Keulen, 1990; Hue et al., 1986; Shen and Shen, 2001) and consequently improve nutrient availability, in particular P.

4.3.4. Soil physical properties

We did not find a significant impact of soil infiltration rate or water holding capacity on yield. This could have been due to a lack of large variation in initial soil physical properties between plots. Manure amendments are expected to improve soil aggregate stability, infiltration rate, and water holding capacity over time through an augmentation of SOM (Dunjana et al., 2012; Rusinamhodzi et al., 2013). It is possible that the added manure was responsible for the greater treatment differentiation seen during the long rainy season when precipitation fell during the latter stages of crop growth. All treatments receiving manure during the long rainy season had significantly higher yields than control plots. This was not seen during the short rainy season when only one treatment (200_67% Org) resulted in significantly higher yields than control, but precipitation was more uniformly distributed. This is perhaps indicative of the added manure improving soil water holding capacity and regulating crop growth during in-season droughts.

5. Conclusion

Better soil fertility management strategies that are specific for given soil types and cropping systems are urgently needed (Singh et al., 2001). We found that combined organic inputs and mineral fertilizer treatments did not always result in significantly higher yields than sole organic inputs in the highly weathered clayey soils of the Lake Victoria Crescent. In addition, differences among combined and sole input treatments disappeared when low N rates were applied. Farmers who use ISFM technology at low application rates typical of the studied region may not see yield differences in the first season of switching from a sole input application to a combined application. Application of mineral fertilizer alone led to yields equivalent to control yields, regardless of application rate. This could have been due to the presence of multiple nutrient deficiencies in the soil or a leaching of N beyond the root zone. We also found that applying combined fertilizer treatments to short duration vegetable crops resulted in low or negative interactive effects. The timing, however, of nutrient release and uptake is important to consider when developing ISFM recommendations and could result in positive interactive effects given the right combination of fertilizer inputs, soil environment and crop. Low farmer participation can potentially erode the yield benefits of fertilizer inputs, which further dampens farmers' enthusiasm for adopting new soil fertility management technologies. On-farm trials offer an opportunity for researchers to test new technologies while accounting for real-world factors such as farmer management. Successful on-farm trials engage farmers as equal partners in the research process.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2016.03.033.

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