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RESEARCH ARTICLE

Forty percent revenue increase by combining organic and mineral nutrient amendments in Ugandan smallholder market vegetable production

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Abstract Linkages between poverty and soil fertility decline in sub-Saharan Africa indicate the need for effective strategies to restore soils, while improving smallholder incomes. Combining organic and inorganic nutrient resources offers a promising means to address this issue, via improvements to nutrient cycling and key soil properties. Yet few studies have examined this practice from an economic perspective and none have explored its potential in intensively managed, market vegetable crops. We address this issue through a demonstrative, on-farm research trial examining the agronomic and economic benefits of mixing manure and inorganic fertilizer for smallholder cabbage production in rural Uganda. Cabbage was grown on eight replicate farms in close association with a farmer field school on vegetable production. Inorganic fertilizer, urea and NPK, and cattle manure were applied alone and in combination, based on equivalent monetary inputs, yielding six treatments: (1) 100 % fertilizer, (2) 75 % fertilizer and 25 % manure, (3) 50 % fertilizer and 50 % manure, (4) 25 % fertilizer and 75 % manure, (5) 100 % manure, and (6) a control without nutrient inputs. Initial soil fertility was evaluated prior to planting and cabbage biomass, nutrient content, and market value were assessed at harvest. Our findings demonstrate that combining manure and inorganic fertilizers produced up to 26 % higher biomass and 40 % higher market value on average than fertilizer or manure alone treatments. Incomes could be increased by 114.68 USD per growing season based on the current area of land that farmers dedicate to cabbage production, compared to using manure or inorganic fertilizer alone. Furthermore, the input ratio of manure to fertilizer appears to be flexible and thus easily adjusted to price fluctuations. This research provides a clear means for smallholder farmers to better allocate soil fertility investments and enhance incomes from market vegetable production. This research also highlights the importance of involving farmers in agricultural research for efficient evaluation of new technologies, building local capacity and yielding rapid impacts.

Keywords *Brassica oleracea* · Integrated soil fertility management · Cattle manure · Nitrogen · Phosphorus

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1 Introduction

Soil fertility remains one of the primary constraints to agricultural productivity in Sub-Saharan Africa (Sanchez 2002) and fertilizer use lags behind other developing regions, with nutrient inputs of inorganic N, P, and K estimated at just 9–15 kg ha^{-1} year^{-1} (Marenya and Barrett 2009). Subsequently, soil nutrient depletion in the region is substantial and greatly exceeds inputs in most cases, despite the fact that many smallholders continue to perceive their soils as fertile (IFDC 2010; Vitousek et al. 2009). In Uganda, the use of fertilizer ranks among the lowest in the world, averaging

3.4 kg ha^{-1} year^{-1}, while 87 % of Ugandans live in rural areas and are primarily reliant on small-scale agriculture (World Bank 2011). Thus, efforts to enhance smallholder farm productivity and soil nutrient reserves through effective soil fertility management offer great potential for reducing poverty and improving livelihoods in Uganda and throughout rural East Africa, yet this work needs to be conducted in close association with farmers so that they understand the benefits of improved soil fertility management firsthand.

While comprising the principle source of nutrient inputs for many smallholders, organic resources such as manures and crop residues are currently insufficient to mitigate nutrient depletion in smallholder farms across much of Africa (Cobo et al. 2010), since the availability of organic inputs is greatly limited by low crop biomass production, competing uses (e.g., fuel, fodder), and high labor requirements for moving and applying organic nutrient inputs (Bationo et al. 2007). Additionally, highly variable residue quality and subsequent variability in decomposition rates and nutrient supply from organic materials represents a key challenge for the optimal management of organic inputs to meet crop nutrient needs.

In light of the limitations associated with organic nutrient inputs, the strategic use of mineral fertilizers offers a promising means to meet crop nutrient demand and help alleviate soil nutrient depletion (Kaizzi et al. 2007; Twomlow et al. 2010). Improving farmer access to fertilizers remains the focus of many development efforts to improve food security and alleviate poverty in the region (e.g., Nziguheba et al. 2010). While high costs, supply chain breakdowns, and other market factors indeed play a role in low fertilizer use and demand across much of Africa, simply improving fertilizer markets will not solve the problem of degraded agricultural soils that dominate the region. For example, Marenya and Barrett (2009) found that market factors were important drivers of fertilizer use for Kenyan farmers with high-quality soils, but much less so for those with poor soils with low soil carbon content. This is likely due to poor response of crop yields to fertilizers in these soils, therefore providing little incentive to increase fertilizer use, even in the presence of favorable fertilizer market conditions. This research suggests that soil biological and physical conditions must first be addressed to justify investment in mineral fertilizer for these farmers.

Research focused on biophysical models for the region has also concluded that market-based efforts to promote fertilizer use should be accompanied by strategies to improve the agronomic efficiency of applied nutrients (Vanlauwe et al. 2011). One such strategy, which lies within the concept of integrated soil fertility management, is the targeted use of mineral fertilizer applied in combination with organic nutrient inputs (Palm et al. 1997). A number of experiments in East and Southern Africa have found improved nutrient use efficiency and other synergies leading to improved yields when mineral and organic nutrient sources are used in combination, especially on degraded soils (Ayaga et al. 2006; Vanlauwe et al. 2011). This strategy recognizes the importance of organic inputs for maintaining soil organic matter (SOM) and biological functioning of soils, while taking advantage of inorganic inputs to improve the synchronization of nutrient supply with crop demand and correct small nutrient imbalances (Palm et al. 1997; Vanlauwe et al. 2011). For example, the application of inorganic fertilizer alone can lead to large losses of N (or fixation of P on mineral surfaces) when available nutrients greatly exceed immediate crop demand, particularly in poor soils with low nutrient holding capacities (and/or high P fixation potential). The addition of organic residues together with inorganic inputs can help to temporarily immobilize available nutrients, thus avoiding losses and releasing them over time to more closely fit crop nutrient demand. Additionally, organic inputs can contribute important nutrients that are not present in common fertilizer blends and enhance other biological and physiochemical soil properties, thus alleviating overall crop growth limitations and potentially improving productivity and nutritional quality. The vast majority of research on this subject, however, has focused on cereals, particularly maize (Chivenge et al. 2011). Whether the benefits of combining organic and inorganic nutrient inputs carry over to more intensively managed market crops, such as vegetables, to which nutrient amendments tend to be preferentially applied (Tittonell et al. 2005; Woomer et al. 1998) and biophysical limitations are more actively managed, remains unclear. Although occupying relatively small areas on most farms in the region, vegetables are of vital importance in rural communities, as they offer a means for smallholder farmers to obtain much needed supplemental income and provide farmers greater opportunity to diversify their diets and improve family nutrition. Despite receiving preferential nutrient additions, indicating the importance of these crops to farmers, fertility inputs often remain inadequate and/or poorly managed.

To address this issue, we conducted an on-farm, demonstrative research trial to assess the potential of combining organic and inorganic nutrient resources for market-based vegetable production. This research was conducted in conjunction with a farmer field school aimed at improving vegetable production in rural Uganda. The specific objectives of the study were to: (1) evaluate how investing in different ratios of purchased mineral and organic nutrient inputs affects cabbage (*Brassica oleracea*) yield, quality, and market value, (2) compare the potential net benefits returned to farmers though different allocations of organic and/or mineral fertilizers, and (3) help build the capacity of farmers to experiment with alternative crops and modes of production.

2 Materials and methods

2.1 Study sites and design

This research was conducted in central Uganda in and around the Nkokonjeru town council (0°14′58″ N; 32°54′ 39″ E), Buikwe district, about 40 km east of Kampala. The site lies within a region commonly referred to as the Lake Victoria Crescent and has a tropical climate moderated by high altitudes (average elevation 1200 m). Average minimum and maximum temperatures range from 15 to 17.5 °C and 25 to 27.5 °C, respectively, and mean annual rainfall is approximately 1,500 mm following a bimodal distribution with peaks in April and November. The region consists of low hills and undulating terrain, with soils dominated by Ferrallitic sandy clay loams (NEMA 1997).

In July of 2010, experimental trials were established on eight farms in a randomized block design, with one replicate per treatment in each block (farm). Farms were selected based on the willingness of host farmers and the interest of farmer groups participating in a concurrently run farmer field school on vegetable production. Research plots were located adjacent to experimental plots associated with the farmer field school and farmers thus regularly participated in management of the plots (e.g., weeding and watering). All farms were located within an 8-km radius and between 1,162 and 1,230 m in elevation. On each farm, 2×2-m adjacent plots were established on a relatively uniform, flat parcel of land and randomly allocated to six soil fertility treatments, representing a replacement design with varying levels of cow manure and inorganic fertilizer. The treatments were: (1) 100 % inorganic fertilizer (100F), (2) 75 % fertilizer and 25 % manure (75F25M), (3) 50 % fertilizer and 50 % manure (50F50M), (4) 25 % fertilizer and 75 % manure (25F75M), (5) 100 % manure (100M), and (6) a control with no nutrient inputs (Table 1). These treatments were standardized, based on equivalent monetary inputs (500 UGX or 0.22 USD per 2×2-m plot; based on 2,290 UGX=USD, on Nov 1, 2010) and recommended N application rates for *B. oleracea* (from 102 to 212 kg N ha^{-1}; Table 1). Prices for manure were based on average values obtained from a survey of 15 farmers in the region, while inorganic fertilizer costs were determined based on the purchase price in Mukono, the nearest commercial center to the study site (45-min bus ride from Nokonjeru).

All plots were hand-tilled using a hoe and manure mixed in (for applicable treatments) to a depth of approximately 20 cm 1 week prior to transplanting. Cabbage seedlings were planted equidistant (50-cm intervals) with 16 plants for each treatment plot on each replicate farm. Inorganic fertilizer was applied according to local practice in two applications at 4 days (15:15:15, N–P–K) and at 20 days (urea) after planting. For both applications, fertilizer granules were applied in a ring around the base of each plant (15-cm diameter) and covered with a thin layer (1–2 cm) of soil. Plots were weeded with a hoe twice during the growing season, while insecticides (cypermetherine and dimethoate) and fungicide (mancozeb) were applied at regular intervals with a backpack sprayer, according to local recommendations. Cabbage was planted to coincide with the August–December rains; however, irrigation was applied (using a watering can with well water) as necessary during the first month after planting due to low precipitation.

2.2 Baseline soil analyses, plant harvest, and yield evaluation

Soils were sampled (0–15 cm) prior to planting, in June 2010, using a small hand trowel and air-dried for lab analyses. Soil samples were sent to the University of California Agriculture and Natural Resources Analytical Laboratory and analyzed for total N and C using the combustion method (AOAC 1997), available phosphorus using the Bray method (Olsen and Sommers 1982), exchangeable potassium, calcium, magnesium, sodium, and estimated cation exchange capacity by displacement with ammonium acetate solution buffered to pH 7.0 (Thomas 1982), pH by saturated paste extract and particle size distribution by hydrometer. A homogenized composite manure sample was analyzed at the Uganda National Agricultural Research Organization (NARO) lab in Kawanda, Uganda for pH (2.5:1 water), OM (Walkley-Black), total N (sulphuric/selenium digestion), extractable P (Mehlich 3), and available bases (K, Ca, and Mg using Mehlich 3 extraction and analyzed with atomic absorption). The quality of manure used in this study was relatively low (7.1 % OM, 0.34 % N), since manure in this region is commonly mixed with considerable quantities of soil during collection and storage.

Harvest was conducted over a 2-week period, following crop maturation at different sites. The four plants in the center of each plot were used for evaluation of yield to avoid edge effects. Plants were cut at the base and immediately weighed for total aboveground fresh biomass. Cabbage heads were then removed from the stem and brought to the local trading center in Nkokonjeru for value appraisal. A group of four local produce retailers considered each head (examining the size, weight, pest damage, color, and general appearance), and came to a consensus on the market value of the cabbage they would offer to a farmer. A wedge sample was then removed from each head and sent to the NARO lab for nutrient analysis. Samples were dried in an oven 70 °C and ground for analysis of N, P, K, Ca,

Table 1 Nutrient application rates for six fertilizer–manure treatment combinations tested in 2010 in Nkokonjeru, Buikwe District, Uganda

Treatment	Application rates [a]			Nutrient inputs		
	Urea [b] (kg ha^{-1})	NPK [b] (kg ha^{-1})	Manure [c] (Mg ha^{-1})	N (kg ha^{-1})	P [d] (kg ha^{-1})	K [d] (kg ha^{-1})
100F	347.25	347.25	0	212	22	43
75F25M	260.50	260.50	7.5	184	19	42
50F50M	173.50	173.50	15.0	156	16	41
25F75M	86.75	86.75	22.5	128	12	40
100M	0	0	30.0	102	9	39
Control	0	0	0	0	0	0

[a] Application rates based on 0.22 USD total fertilizer and/or manure costs per 2×2-m plot. For example, 75F25M indicates that 75 % of the cost was spent on fertilizer and 25 % of the cost was spent on manure

[b] Urea (46 %N) and NPK (15:15:15)=0.79 USD kg^{-1}

[c] Dried cow manure=0.87 USD 48 kg^{-1} (approximately one wheelbarrow load)

[d] P and K for manure additions based on extractable nutrients (not totals)

and Mg in the plant tissue according to Parkinson and Allen (1975).

2.3 Data analysis

Treatment means for aboveground biomass and cabbage market value were compared in ANOVA, with treatment as the main factor and farms treated as blocks and considered a random variable. Market value data was transformed using a power transformation in order to meet the assumptions of ANOVA (i.e., normality and homogeneity of variance). Individual treatments were compared to the control and pairwise comparisons were made using the Tukey HSD test. The LS Means function was used to account for several missing data points as a result of the loss of several cabbages due to factors deemed unrelated to the soil fertility treatments (e.g., disturbance by animals). Additionally, orthogonal contrasts were used to compare the three combination treatments (75F25M, 50F50M, 25F75M) with the manure-only (100M) and mineral fertilizer-only (100F) treatments for both biomass and market value results. Finally, initial soil properties for each location were regressed with average plant biomass across the eight farms for each treatment. All data was analyzed using SAS software (SAS Institute 2008).

A simple cost–benefit analysis was also carried out to compare the estimated net benefits of the different fertility treatments. Costs were equal for all plots, except the control (with no nutrient inputs), and benefits were calculated based on the average market value of cabbage in each treatment. Net benefits were calculated by subtracting the average value of cabbage in each treatment by the cost of soil fertility amendment (0.22 USD per plot). These values were then expressed in terms of percent increase in net benefits relative to the control.

3 Results and discussion

3.1 Soil fertility and management impacts on cabbage growth

All five treatments receiving nutrient amendments demonstrated significantly higher biomass and market value for cabbage heads when compared to the control ($P<0.01$; Table 2). In fact, almost no fully formed heads were observed in the control plots suggesting that some level of nutrient input is required for cabbage production in these soils. The greatest plant growth and market values were observed in the three combination treatments (25F75M, 50F50M, and 75F25M). Individual pairwise comparisons showed that the 25F75M and 75F25M treatments both produced cabbages of significantly higher value than the 100F treatment ($P<0.05$). There were no significant differences in value between the 100M treatment and any of the combination treatments or between the 100F and 100M treatments. However, orthogonal contrasts revealed that the average for the three combination treatments taken together produced cabbages with a significantly higher average market value (per head) compared to the 100F or 100M treatments ($P<0.001$ and $P=0.012$, respectively; Fig. 1). Mean aboveground biomass in each plot was also greater in the combination treatments, but only significantly when compared to the 100F treatment ($P=0.004$). There were no

Table 2 Mean biomass and market value of cabbage production (*B. oleracea*) under six fertilizer–manure treatment combinations tested in 2010 in Nkokonjeru, Buikwe District, Uganda

Treatment	Plant biomass[a] (kg/plot)			Market value[b] (USD/plot)			Net benefit (USD/plot)	Increase in benefit over control, %
100F	21.9	*4.8*	a	1.09	*0.21*	a	0.87	71
100M	25.1	*2.6*	a	1.23	*0.34*	ab	1.01	98
25F75M	27.4	*2.8*	a	1.64	*0.24*	b	1.42	179
50F50M	28.5	*3.6*	a	1.55	*0.36*	ab	1.34	162
75F25M	26.9	*2.4*	a	1.68	*0.16*	b	1.46	186
C	12.3	*3.2*	b	0.51	*0.25*	c	0.51	0

Values in italics to the right of means for plant biomass and market value, while treatments with different lowercase letters represent significantly ($P<0.05$) different values according to Turkey's HSD test

[a] Fresh weight biomass per plot (2×2 m) upon harvest

[b] Average per plot (2×2 m) market value

significant differences in biomass or market value observed among the three combination treatments.

Soil analyses for each location showed substantial variability across farms for certain soil properties, namely available P and K as well as pH (see Table 3). Significant correlations were thus observed between initial soil P and K availability and average plant biomass production ($R^2>0.5$; $P<0.05$; data not shown). Examining individual treatments across farms, we found that the positive correlation of cabbage biomass with initial soil P and K was strongest for the 100F treatment ($P=0.015$ and $P=0.026$, respectively) and diminished in treatments as the proportion of manure increased. Results from plant tissue sample analyses suggested critical deficiencies of P (Hochmuth et al. 2009) for the 100F and control treatments, but not in the treatments with manure. No critical deficiencies for K, Ca, or Mg (Hochmuth et al. 2009) were observed in any of the treatments (data not shown).

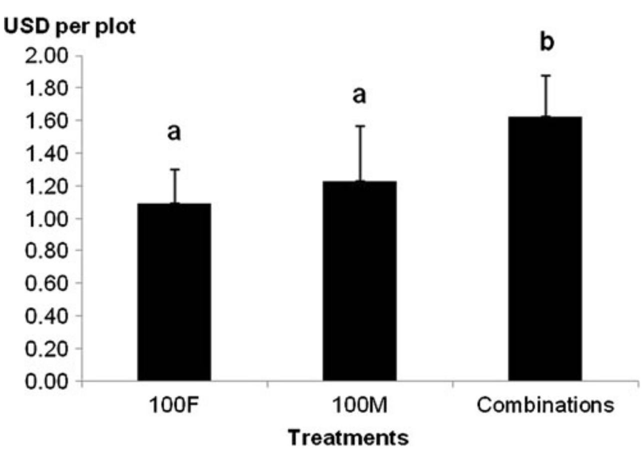

Fig. 1 Comparison of cabbage market value for inorganic fertilizer alone (100F), manure alone (100M) and manure–fertilizer combination treatments tested in 2010 in Nkokonjeru, Buikwe District, Uganda (*error bars* represent the standard error of the mean, while *lowercase letters above each error bar* indicate statistically significant differences between treatments ($P<0.05$) according to orthogonal contrasts)

We found a lack of correlation between cabbage production and nutrient inputs for the five treatments receiving nutrient amendments. While this could indicate that inputs exceeded the response curve of cabbage, we note that the manure-dominated treatments (100M and 25F75M) had relatively low inputs of N and P (Table 1) and suggest that this is unlikely. Given that the observed differences in crop growth appear not to be related to the total amount of nutrients applied, the higher production observed in the combination treatments indicates a positive interaction between inorganic fertilizer and manure. Based on our results and those of similar studies in the literature (discussed below), we identify several potential mechanisms to explain this synergy. The P deficiencies observed for cabbage growing in the control and 100F treatments together with the overall correlation between initial P availability and cabbage production (data not presented), suggest that P likely plays an important role in the treatment effects observed via orthogonal contrasts (Fig. 1). While not significant, we note that P uptake was generally higher among the combined manure–fertilizer treatments. The apparent role of organic matter in alleviating P deficiencies is further emphasized by the increasing strength of correlations between initial P status and biomass production with decreasing manure inputs. A number of studies suggest that application of manure (or organic matter in general) can improve plant P nutrition in tropical soils via physiochemical effects on P availability and increased microbial activity, leading to the enhanced biological cycling of P. For example, Nziguheba et al. (1998) found that the addition of high-quality organic matter decreased the P adsorption capacity of kaolinitic clay loams in Western Kenya, likely because organic matter competed with phosphate anions for adsorption sites, making the latter more available for plant uptake. Manure has also been shown to raise the pH of soil (Mugwe et al. 2009),

Table 3 Selected properties for surface soils (0–15 cm) on eight replicate farms in Nkokonjeru, Buikwe District, Uganda

Location	Total C g kg^{-1}	Total N	Bray-P	Exchangeable K	CEC mEq 100 g^{-1}	pH	Sand %	Silt %	Clay %
Ndolwa	25.6	2.29	0.016	0.324	8.06	5.47	42	18	40
Mayirikiti	21.5	1.78	0.006	0.051	9.59	5.95	45	15	40
Mulajje	20.6	1.63	0.049	0.327	10.28	6.26	51	16	33
Naziwanga	23.9	2.07	0.007	0.081	9.89	5.71	42	13	45
Bukasa	12.7	1.13	0.008	0.173	3.45	5.11	51	14	35
Masaba	21.8	1.80	0.006	0.109	7.85	5.57	48	15	37
Kwerimidde	16.2	1.36	0.007	0.087	5.35	5.33	58	13	29
Nyemerwa	23.2	1.91	0.007	0.392	7.51	5.49	38	28	34

thus potentially decreasing the adsorption capacity of Al and releasing P back into solution for use by plants. In addition to reducing P fixation, it has been shown that combining organic and inorganic P sources can increase microbial biomass P (Nziguheba et al. 1998), a major source of plant available P in many tropical soils (Oberson et al. 2006). Immobilization of P by soil microbes maintains it in a biologically active pool where P can be more easily recovered by plants (relative to P that is fixed on mineral surfaces). Corroborating this idea, Ayaga et al. (2006) observed that higher maize yields were correlated with increased microbial biomass P when applying a combination of farmyard manure and mineral P fertilizer, especially on P-fixing soils. At the same time, additions of inorganic N in the presence of organic inputs, may accelerate decomposition processes and release more P for plant uptake.

Along with beneficial impacts on P cycling, increases in microbial biomass that are often associated with organic matter additions can reduce the losses of reactive N and potentially improve the synchrony of N supply with plant demand (Palm et al. 1997; Kramer et al. 2002). In agreement with our findings, Vanlauwe et al. (2011) reviewed studies from a range of sites in southern and eastern Africa and found that mixing inorganic fertilizer with manure or compost provided the greatest N-use efficiencies compared to other types of organic residues or mineral fertilizer alone. They attributed this effect in part to temporary immobilization (and subsequent release) of inorganic N additions. However, a lack of significant differences for total plant N uptake between the 100F and combination treatments ($P > 0.05$; data not presented) suggests that this mechanism is perhaps less important in our study. While impacts on nutrient cycling are clearly important, the benefits of mixing inorganic fertilizer with manure may also be related to short-term improvements in other soil properties, similar to those associated with long-term increases in SOM (i.e., improved soil structure, water dynamics and soil faunal activity; Lavelle et al. 2001; Vanlauwe et al. 2001).

While the potential benefits of combining organic and mineral nutrient resources are clearly demonstrated in this research, extrapolation of our findings to other regions or new contexts must be considered with some level of caution. For example, yield increases associated with the mixing of organic and inorganic nutrient resources are likely to depend greatly on soil type and the management history of a particular plot, with less fertile sandy soils likely to benefit most from this practice (Zingore et al. 2007; Chivenge et al. 2011). Additionally, the quality of available organic resources can vary considerably across sites, thus greatly influencing nutrient dynamics and the benefit of combining nutrient inputs to crops (Palm et al. 1997). Although including more farms or field sites may have strengthened our findings, we examined eight distinct farms distributed across the Nkokonjeru township and demonstrated statistically significant impacts of combining mineral and organic nutrient resources. Thus, we feel that the results of this study are fairly robust and suggest that, on average, adoption of such practices would greatly benefit farmers growing cabbage (and potentially other vegetables) for market production in the region. It must also be noted that this research represents only a single growing season and thus, we cannot be certain that the observed effect would be consistent from one year to the next. However, we point out that significant results were obtained after only one growing season and argue that the benefits of this practice are likely to increase over time as continual application of organic residues contributes to stable SOM and improved soil functioning (Fig. 2).

3.2 Farmer benefits, management implications, and potential for impact

A simple cost–benefit analysis showed that all treatments resulted in a substantial increase in economic benefits compared to the control, ranging from a 71 % increase in the 100F treatment to a 186 % increase under 75F25M. The average net benefit of the three combination treatments was

Fig. 2 Farmer field school group discussing field trial at one of the replicate farms in 2010 in Nkokonjeru, Buikwe District, Uganda

61 and 39 % greater than that of the 100F and 100M treatments; respectively. The total increase in benefits over the control for the combination treatments were approximately double that observed for the 100F and 100M treatments (Table 2). Thus, an increase in the value of cabbages grown with the combined application of manure and inorganic fertilizers could contribute significantly to improving smallholder incomes in the region. A survey of 32 farmers growing cabbage in the Buikwe district found an average area of 990 m^2 dedicated to cabbage production on each farm (unpublished data). Extrapolating the results of our experiment to this average-sized cabbage field, we found that for the same investment in soil fertility (54.04 USD per field), cabbage revenue could be increase from 269.78 and 304.43 USD per field with fertilizer or manure alone to an average of 401.78 USD per field when these nutrient inputs are applied in combination. We note that this average increase of 114.68 USD per field per growing is highly significant compared to the per capita income in Uganda of roughly 500 USD $year^{-1}$ (World Bank 2011). Even if farmers cannot initially afford to apply nutrient inputs and manage their entire fields at the level of inputs tested in this study, investment in smaller areas could still yield substantial increases in income.

While both manure and mineral fertilizer are relatively available in the region, it is important to note that the relative costs of each will fluctuate over time. However, the lack of significant differences in biomass and market value observed among the combination treatments suggests there is no substantial difference in the net benefits obtained from the three ratios tested. Thus, even though farmers' access to mineral fertilizers and manure may vary over time or across the region, farmers could theoretically respond to price changes by adjusting the ratio of manure to mineral fertilizer applied without seeing significant decreases in cabbage yield or market value. Given this flexibility and the demonstrated economic benefit of combining organic and inorganic nutrient sources, the potential for farmer adoption appears to be high. Large-scale implementation of this integrated soil fertility management strategy could lead to an increased focus on market production and subsequent investment in restoring SOM and the nutrient capital of soils. Ideally, market vegetables could be rotated with less intensively managed crops to avoid pest and disease issues, while supporting soil fertility for lower value subsistence crops that are also vital to farming families.

From a development standpoint, the close interaction between this research and the farmer field school, conducting farmer-led research adjacent to our plots, yielded important synergies that contributed both to the relevance of our research and the impact of the farmer engagement activities. While not responsible for the research plots, farmers participated significantly in their management and followed the progress of our experiment with great interest. Farmers were introduced to the goals and study approach of this experiment from the beginning and were observed to adopt similar cabbage production techniques (particularly with regards to fertilization) within the same field season. For the most part, we note that treatment differences were visually identifiable for farmers and reinforced the need for them to consider alternative fertilization strategies. Additional farmer engagement activities at the end of this experiment permitted us to share summary results from all farms and to clearly demonstrate the potential benefits of mixing organic and inorganic nutrient resources.

4 Summary and conclusions

The findings presented here are among the first to suggest that combining organic and inorganic nutrient amendments is a promising strategy for improving smallholder incomes derived from market vegetable production on soils in sub-Saharan Africa. Our findings corroborate the results of previous research showing that biophysical synergies from combining organic and inorganic nutrient sources can improve nutrient availability and crop production. Furthermore, the results of our study are novel in demonstrating that these synergies can in fact lead to a substantial increase in economic benefits to farmers when considering equivalent economic investment in fertility inputs. While increases in plant growth were observed, the main benefit of combining organic and inorganic nutrient sources over manure or inorganic fertilizer alone was higher cabbage market value, despite lower overall inputs relative to the fertilizer alone treatment. Results for soil and plant tissue analyses suggest that improvements to cabbage production resulted, at least in part, from increased P availability in the presence of manure, along with contributions of available N from the inorganic fertilizer. However, improvements to other soil properties (e.g., structure, water storage, biological activity) may have also played an important role.

Applying a simple cost–benefit analysis, we demonstrated that net benefits of mixing manure and inorganic fertilizer (increases relative to the control), were on average 61 and 39 % greater than for the application of fertilizer or manure alone. Meanwhile, the lack of a significant difference between the three ratios of combined organic and inorganic inputs indicates that the ecological mechanisms behind this phenomenon are flexible, thus greatly simplifying management considerations and increasing the potential for adoption of this technology under a range of soil fertility input prices. Conducting this experiment on farmers' land concurrent with a farmer field school on vegetable production provided for significant stakeholder interaction in this research. Although impact was not formally evaluated in this study, there were clear indications that farmers became aware of the benefits of combining organic and inorganic nutrient source and were open to adopting such technologies. We suggest that simple, yet controlled experimentation within future outreach programs could be an efficient and effective approach to further test the benefits of integrated soil fertility management strategies (and other technologies), while simultaneously disseminating results to and building the capacity of smallholder farmers.

This research is unique in that we worked closely with farmers to demonstrate clear agronomic and economic benefits of combining organic and inorganic nutrient resources within an intensively managed market vegetable system. Despite the great promise in these findings, we feel that additional research would be useful to further elucidate: (1) if an optimal ratio (or total amount) of inorganic and organic nutrient inputs exists; (2) how this might vary under different management regimes, climatic conditions, soil types or with organic resources of differing quality; (3) the impacts of this integrated soil fertility management strategy on long-term productivity; and (4) the potential for applying this technology to other high value crops in the region.

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References

AOAC (1997) Method 972.43, microchemical determination of carbon, hydrogen, and nitrogen. Official methods of analysis, 16th edition. AOAC International, Arlington, VA

Ayaga G, Todd A, Brookes PC (2006) Enhanced biological cycling of phosphorus increases its availability to crops in low-input sub-Saharan farming systems. Soil Biol Biochem 38:81–90. doi:10.1016/j.soilbio.2005.04.019

Bationo A, Kihara J, Vanlauwe B, Waswa B, Kimetu J (2007) Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agric Syst 94:13–25. doi:10.1016/j.agsy.2005.08.011

Chivenge P, Vanlauwe B, Six J (2011) Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis. Plant Soil 342:1–30. doi:10.1007/s11104-010-0626-5

Cobo JG, Dercon G, Cadisch G (2010) Nutrient balances in African land use systems across different spatial scales: a review of approaches, challenges and progress. Agric Ecosyst Environ 136:1–15. doi:10.1016/j.agee.2009.11.006

Hochmuth G, Maynard D, Vavrina C, Hanlon E, Simonne E (2009) Plant tissue analysis and interpretation for vegetable crops in Florida. The Institute of Food and Agricultural Sciences, University of Florida, Gainsville

IFDC (2010) Growing food…changing lives: 2010 Annual Report. IDRC, Muscle Shoals, AL

SAS Institute (2008) SAS Software Version 9.1.3. SAS Institute, Cary, N.C.

Kaizzi KC, Byalebeka J, Wortmann CS, Mamo M (2007) Low input approaches for soil fertility management in semiarid eastern Uganda. Agron J 99:847–853. doi:10.2134/agronj2006.0238

Kramer AW, Doane TA, Horwath WR, van Kessel C (2002) Combining fertilizer and organic inputs to synchronize N supply in alternative cropping systems in California. Agric Ecosyst Environ 9:233–243. doi:10.1016/S0167-8809(01)00226-2

Lavelle P, Barros E, Blanchart E, Brown G, Desjardins T, Mariani L, Rossi JP (2001) SOM management in the tropics: why feeding the soil macrofauna? Nutr Cycl Agroecosyst 61:53–61. doi:10.1023/A:1013368715742

Marenya PP, Barrett CB (2009) Soil quality and fertilizer use rates among smallholder farmers in western Kenya. Agric Econ 40:561–572. doi:10.1111/j.1574-0862.2009.00398.x

Mugwe J, Mugendi D, Mucheru-Muna M, Odee D, Mairura F (2009) Effect of selected organic materials and inorganic fertilizer on the soil fertility of a Humic Nitisol in the central highlands of Kenya. Soil Use Manag 25:434–440. doi:10.1111/j.1475-2743.2009.00244.x

NEMA (1997) District State of Environment Report for Mukono District, Uganda. National Environment Management Authority

Nziguheba G, Palm CA, Buresh RJ, Smithson PC (1998) Soil phosphorus fractions and adsorption as a affected by organic and inorganic sources. Plant Soil 198:159–168. doi:10.1023/A:1004389704235

Nziguheba G et al (2010) The African green revolution: results from the millenium villages project. Adv Agron 109:76–115. doi:10.1016/S0065-2113(10)09003-6

Oberson A, Bünemann EK, Friesen DK, Rao IM, Smithson PC, Turner BL, Frossard E (2006) Improving phosphorus fertility in tropical soils through biological interventions. In: Uphoff N et al (eds) Biological approaches to sustainable soil systems. CRC, Boca Raton, pp 531–546

Olsen SR, Sommers LE (1982) Phosphorus. In: Page AL, Miller RH, Keeney DR (eds) Methods of soil analysis, part 2. Chemical and microbiological properties. ASA, Madison, pp 403–430

Palm CA, Myers RK, Nandwa SM (1997) Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. In: Buresh RJ, Sanchez PA, Calhoun F (eds) Replenishing soil fertility in Africa. Soil Science Society of America, Madison, pp 193–218

Parkinson JA, Allen SE (1975) A wet oxidation procedure suitable for the determination of nitrogen and mineral nutrients in biological material. Commun Soil Sci Plant Anal 6:1–11. doi:10.1080/00103627509366539

Sanchez (2002) Soil fertility and hunger in Africa. Science 295:2019–2020. doi:10.1126/science.1065256

Thomas GW (1982) Exchangeable cations. In: Page AL (ed) Methods of soil analysis. Part 2. Chemical and microbiological properties. ASA, Madison, pp 159–165

Tittonell P, Vanlauwe B, Leffelaar PA, Shepherd KD, Giller KE (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. Agric Ecosyst Environ 110:166–184. doi:10.1016/j.agee.2005.04.003

Twomlow S, Rohrbach D, Dimes J, Rusike J, Mupangwa W, Ncube B, Hove L, Moyo M, Mashingaidze N, Mahposa P (2010) Micro-dosing as a pathway to Africa's green revolution: evidence from broad-scale on-farm trials. Nutr Cycl Agroecosyst 88:3–15. doi:10.1007/s10705-008-9200-4

Vanlauwe B, Aihou K, Aman S, Iwuafor ENO, Tossah BK, Diels J, Sanginga N, Lyasse O, Merckx R, Deckers D (2001) Maize yield as affected by organic inputs and urea in the West African moist savanna. Agron J 93:1191–1199. doi:10.2134/agronj2001.1191

Vanlauwe B, Kihara J, Chivenge P, Pypers P, Coe R, 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

Vitousek PM et al (2009) Nutrient imbalances in agricultural development. Science 324:1519–1520. doi:10.1126/science.1170261

Woomer P, Bekunda M, Karanja NK, Moorehouse T, Okalebo JR (1998) Agricultural resource management by smallholder farmers in East Africa. Nat Resour 34:22–33

World Bank (2011) Datasets: rural population (% of total population) from 2009 and Fertilizer consumption (kg per ha of arable land) from 2008. from http://data.worldbank.org/indicator. Accessed 16 June 2011

Zingore S, Murwira HK, Delve RJ, Giller KE (2007) Soil type, management history and current resource allocation: three dimensions regulating variability in crop productivity on African smallholder farms. Field Crops Res 101:296–305. doi:10.1016/j.fcr.2006.12.006