Exploring on-farm additive common bean yield potential to organic and mineral fertilizers on contrasting soils of Buganda Catena, Central Uganda

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Mineral and organic fertilizers have great potential to enhance crop yields in low fertility soils of the Buganda catena. However, the need for site-specific knowledge on use and yield of the two fertilizer types in a complex soil scape is acute among smallholder farmers exploiting any soil differences. This study evaluated on-farm grain yield response of common bean (\textit{Phaseolus vulgaris} L.) to organic and mineral N and P fertilizers on three soils. Treatments included poultry manure at 0, 2.5 and 5.0 t ha\textsuperscript{-1}, and N and P each at 0, 7.5, and 15 kg ha\textsuperscript{-1} in a complete factorial for two rainy seasons on each of the local farmers’ soils classified as Phaeozem, Cambisol, and Umbrisol. Fertilizer application resulted in 20, 25 and 36\% maxima grain yield increase relative to soils (Phaeozem, Cambisol and Umbrisol soil, respectively) potentials when no nutrient inputs is applied. Mineral fertilizers applied separately reduced yield on the Cambisol while on Umbrisol soil, there was no particular increase; hence these were risky applications on highly degraded soils. Yield increases were greater with manure, with or without mineral fertilizers, but yield increase was not particularly fundamental on Phaeozem sites but was on Cambisol and marginal on the Umbrisol, resulting into positive and negative interaction effects, respectively. Thus, soil specific rates of manure nutrient ratios or with N and P mineral fertilizers are an effective strategy for targeting improved common bean yield under indigenous soil taxonomy of Buganda catena soils.

\textbf{Key words:} \textit{Phaseolus vulgaris} L, integrated soil fertility management, smallholder farming, soil type.

\textbf{INTRODUCTION}

Common beans (\textit{Phaseolus vulgaris} L.) are vital for nutrition security and considered a cost-effective option

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for improving the diets of low-income consumers in developing countries. Annual per capita bean consumption in Uganda is second worldwide after Rwanda and is about 9.8 kg, contributing 12 and 4% of the total protein and calorie requirements, respectively, per person (Larochelle et al., 2016). Besides food security, nutrition and health sustainable development goals (Larochelle et al., 2016), common beans contribute to biological nitrogen fixation (BNF) (Kabahuma, 2013; Gunnabo et al., 2019) and poverty reduction among small landholders who grow them for market. However, production of common beans is below the average potential of 2000 kg ha\(^{-1}\) (Goetsch et al., 2016). Low bean productivity emanates among others from inherently low soil fertility coupled with low and poor use of land productivity enhancing inputs (Larochelle et al., 2016).

Soil use and management is a major determinant of the food self-sufficiency and income of smallholder farmers in sub-Saharan Africa (SSA). Improving productivity of poorly fertile soils in farming system remains a major concern. With increasing land pressure, complex farming systems and accelerated climate change impacts, Integrated Soil Fertility Management (ISFM) which includes use of both mineral and organic fertilizers, improved seeds and locally adapted practices, is at the forefront for increasing yields. Both organic and mineral fertilizers are comparatively expensive and often inadequate for application in farmers’ degraded plots (Mugwe et al., 2009). Degraded soils are often deficient in nitrogen (N), phosphorus (P), and potassium (K) (Stoorvogel and Smaling, 1990; Morris et al., 2007; MAAIF, 2016), and other nutrients resulting in poor crop yields. Yield losses are particularly severe for annual crops (Semalulu et al., 2012; Apanovich and Lenssen, 2018), including common bean (Place et al., 2003; Goetsch et al., 2016, 2017) where N and P deficiencies limit production (Wortmann et al., 1998; Kyomuhendo et al., 2018).

Improving productivity through soil fertility management is largely by use of inorganic fertilizers. Mueller et al. (2012) closed the yield gap by 73% using considerable amounts of N, P\(_2\)O\(_5\) and K\(_2\)O fertilizers. However, the rate of nutrient application in SSA is about 10 kg total nutrients ha\(^{-1}\) (Fairhurst et al., 2012), an inadequate amount for degraded soils. In Uganda, fertilizer use is estimated to supply about 1.0 kg of nutrients ha\(^{-1}\) (Morris et al., 2007; MAAIF, 2016). This is because few fertilizers are imported and the majority of smallholder farmers lack the financial resources to purchase them. Using more available organic fertilizers was found to be economically attractive to farmers (Sanchez, 1997) but is challenged by unbalanced nutrient supply to crops (Silesi et al., 2016). This may deplete other nutrients and reduce fertilizer efficiency over time. Therefore, providing fertilizers in a balanced nutrient management program may improve crop productivity and smallholder farmer buy-in.

Combined application of organic with mineral nutrient sources has been a good option to increase fertilizer use, efficiency and productivity. Combined applications can improve synchronization of nutrient availability and subsequent uptake by the crop (Ayuke et al., 2004), especially when the levels applied are low (Kapkiyai et al., 1999). Some studies reported greater yield increase than when either fertilizer type was applied alone at a nutrient rate equivalent to the combination (Chivenge et al., 2009; Bekunda et al., 2010; Pincus et al., 2016). Muyayabantu et al. (2012) reported greater maize (Zea mays L) yield with increasing rates of farmyard manure application. However, grain yields above 3.5 t ha\(^{-1}\) were only obtained when both farmyard manure and inorganic N and P fertilizers were applied. In contrast, some studies indicate higher yield with sole organic than inorganic and combinations of inorganic and manure (Mucheru-Muna et al., 2013). These differences in response to fertilizer combinations may result from many factors including genotype and large heterogeneity in local soil fertility. Thus, farmer buy-in of fertilizer packages may also require understanding relative grain yield based on genotypic potential under diverse environments and soil management levels.

Although many studies continue reporting different productivity from combined fertilizer use, adaptations to highly variable biophysical and agro ecological conditions receive limited attention. Soils vary in their responsiveness to fertilizers with farmers expecting positive returns from try-outs for continued use. For example, Bagula et al. (2014) reported yield differences from 52 and 190% observed among soils and fertilizer treatments. Reducing this variability require understanding the added yield benefits from fertilizer combination relative to a crop potential on a given soil. This enables farmers to make adoptive fertilizer use decisions based on yield targets, resource availability and risk aversion (Lambrecht et al., 2014). Understanding specific fertilizer options for each soil would therefore reduce the observed yield variability while increasing beneficial returns from organic and mineral fertilizer use. This in turn saves on fertilizer use and affects efficiency and technology uptake. Improved yield with reduced variability further leads to stable food supply and farmer income (Ray et al., 2015). Therefore, the objective of this study was to determine the on-farm additive effect of organic and mineral fertilizers for common bean grain (P. vulgaris L.) yield on contrasting soils.

MATERIALS AND METHODS

Study area

On-farm demonstration trials were conducted in Masaka district, south central Uganda, in the tropical wet and dry or savanna
In this region, agriculture is rain-fed with average annual precipitation of about 1350 mm in a bi-modal distribution. The main rainy seasons are the months of March-May (Season A) and August-November (season B). Annual mean temperature varies between 16 and 27°C with an average of about 21°C. Temperature, humidity and wind patterns display relatively small variations throughout the year in Lake Victoria crescent zone where Masaka is located. Farmers in this area distinguish three local soil types commonly cropped to beans by their crops. However, a few farmers spray urea solution to young growing bean plants. Poultry, cattle, goats and pigs are the main livestock from which farmers obtain manure to fertilize their crops. Other mineral fertilizers like diammonium phosphate (DAP) and organic fertilizers are targeted to companion maize plants at planting from which intercropped beans may benefit.

### Soil sampling and analysis

Immediately after site identification, but before land preparation, soil samples were collected from 0 to 15-cm depth using an auger to evaluate soil chemical and physical characteristics. The collected soil samples were taken in a zigzag pattern from five different places in each field and composited into one sample. Soils were analyzed at the National Agricultural Research Laboratories, Kawanda, Uganda for pH, organic carbon (OC), N, P, K, calcium (Ca) and magnesium (Mg) using standard methods described in Okalebo et al. (2002) and results presented (Table 1). The wet oxidation method of Walkley and Black (Nelson and Sommers, 1982) was used for soil organic carbon determination. Total soil N was measured following Kjeldahl digestion (Okalebo et al., 2002). Available P was determined using Mehlich 3 solution (Mehlich, 1984). For each season, a composite manure sample was analyzed at Kawanda for moisture concentration, pH, OC, N, and Mehlich 3 extractable P, K, Ca and Mg. The obtained manure nutrient concentrations are presented in Table 2.

### On-farm trials

On-farm trials were carried out during the first and second rain of 2015 (seasons 2015A and B) on each of the three soils. In each season, experimental locations were changed, but all were previously cultivated to maize a season before set up. All three soils were deficient in N and P (Table 1). Soil pH was low for Cambisol and Umbrisol soils but only slightly acidic for Phaeozem soil. These soils exhibited low OC concentration that was below preferred levels (Table 1). The Phaeozem and Umbrisol site had comparatively high available K, but Ca and Mg were low on all soils (Table 1). Prior to initiating any treatments, each site was ploughed twice using a heavy hand hoe. At the onset of rains, experiments

### Table 1. Means for selected properties of the three farmer defined soil types.

| Property     | Phaeozem | Cambisol | Umbrisol | F-test | Critical values |
|--------------|----------|----------|----------|--------|-----------------|
| pH           | 6.4±0.2  | 5.2±0.08 | 5.5±0.3  | 0.003  | 5.5*            |
| SOC (%)      | 2.7±0.4  | 2.5±0.1  | 2.4±0.2  | 0.598  | 3.0*            |
| N (%)        | 0.203±0.004 | 0.175±0.001 | 0.196±0.002 | 0.001  | 0.250*          |
| P (mg/kg)    | 14.3±2.6 | 4.2±0.6  | 12.6±3.4 | 0.016  | 15.0*           |
| K (cmol(+)/kg)| 0.49±0.15 | 0.14±0.02  | 0.45±0.01  | 0.051  | 0.15*           |
| Ca (cmol(+)/kg)| 2.41±0.37 | 0.86±0.13   | 1.01±0.27  | 0.002  | 4.50*         |
| Mg (cmol(+)/kg)| 1.74±0.03 | 0.8±0.20    | 1.06±0.23  | 0.009  | 2.00*         |
| Sand (%)     | 56.0±2.4 | 53±1.9   | 56.5±3.2 | 0.497  | -              |
| Clay (%)     | 31.8±2.5 | 39±1.9    | 35.5±3.2 | 0.121  | -              |
| Silt (%)     | 12.3±0.63 | 8.0±0.0   | 8.0±0.0  | 0.001  | -              |

Significant effect (P < 0.05).

Source: *Schwartz and Pastor-Corrales (1989) and Okalebo et al. (2002).

### Table 2. Chemical characteristics of applied chicken manure on dry matter basis.

| Parameter     | pH  | OM (%) | N (%) | P (%) | Ca (%) | Mg (%) | K (%) |
|---------------|-----|--------|-------|-------|--------|--------|-------|
| Chicken manure| 7.2 | 22.4   | 1.43  | 0.10  | 0.26   | 0.07   | 0.02  |

Climate, in this region, agriculture is rain-fed with average annual precipitation of about 1350 mm in a bi-modal distribution. The main rainy seasons are the months of March-May (Season A) and August-November (season B). Annual mean temperature varies between 16 and 27°C with an average of about 21°C. Temperature, humidity and wind patterns display relatively small variations throughout the year in Lake Victoria crescent zone where Masaka is located. Farmers in this area distinguish three local soil types commonly cropped to beans by their crops. However, a few farmers spray urea solution to young growing bean plants. Poultry, cattle, goats and pigs are the main livestock from which farmers obtain manure to fertilize their crops. However, a few farmers benefit from compost heaps from plant and animal waste as fertilizers. Depending on the season, farmers plant common beans once or twice per annum either as a mono crop or intercrop depending on the purpose. However, beans are mainly cultivated for food consumption during 'A' season with a few farmers cultivating for commercial purposes in 'B' season. In both seasons, either mineral or organic fertilizer, mainly chicken manure, may be applied, but rarely is this done by smallholders. Mineral fertilizers, also referred to as inorganic fertilizers, are rarely applied to beans, but a few farmers spray urea solution to young growing bean plants. Other mineral fertilizers like diammonium phosphate (DAP) and organic fertilizers are targeted to companion maize plants at planting from which intercropped beans may benefit.
were laid out in a randomized complete block design (RCBD) in a factorial arrangement of mineral N and P fertilizer and manure application on each of the three soils. There were three replications of each treatment at each site in each season. The N and P fertilizer rates were 0.0, 7.5, and 15.0 kg N and P ha\(^{-1}\) each. The N was applied as urea and P as triple super phosphate (TSP). Composted poultry manure (layer chickens) (Table 2) was obtained from a local farmer in A and B seasons and applied at 0.0, 2.5, and 5.0 t ha\(^{-1}\). Both mineral and organic fertilizers were basal broadcasted in appropriate plots then incorporated into soil using a hand hoe. At a spacing of 50 cm between rows and 15 cm within rows, two seeds of K131 common bean (Nkonya, 2001) were planted per hole on 7th April and 15th September for the 2015 A and B seasons, respectively. Plots were hand-weeded during the second, fourth and sixth week after planting (WAP). Where weeds occurred after the sixth week, they were hand-pulled to preclude confounding weed competition with fertility treatments. Due to high pest prevalence, farmers sprayed the bean plants against aphids, flower thrips and caterpillars using formulated dimethoate on a weekly basis from the second WAP up to flowering and twice from pod formation to maturity.

### Data collection

Bean plants were hand-harvested at maturity, when all pods were dry. Harvesting started on 27th July 2015 for Phaeozem and 1st August for Cambisol and Umbrisol in Season A. In 2015B season, harvesting was on 19th, 20th, and 21st December for the Phaeozem, Umbrisol and Cambisol sites, respectively. In each plot, the number of plants harvested from the three middle rows for 1.2-m was counted and threshed. The threshed samples were winnowed, sorted for further removal of foreign materials, and grains weighed using \pm 0.001 kg weighing balance. A sub-sample of 80 g bean grains was oven-dried at 72°C to determine dry matter yield at 12.5% moisture basis.

### Statistical analysis

The mean effect of inorganic N, P and chicken manure on bean grain yield was analyzed using a generalized linear model analysis of variance with Genstat 12.1. Yields were averaged across the two seasons. Fertilizer treatments and soils were included in the model as variables and tested for their interactions. Due to differences, soils were analyzed separately for fertilizer application effects on yield. Prior to any statistical analysis, data were tested for normality and homogeneity of variance using Cook's statistics (Payne et al., 2009). Fisher's protected Least Significant Difference (LSD) at 0.05 probability level was used to separate means when significant differences were evident. Using mean yield from fertilizer combinations, relative yield increase (added yield due to fertilizer application) resulting from fertilizer application of planted variety was calculated according to Equation 1:

\[
\text{Relative yield (\%)},\ R = \frac{(\text{Yield in fertilized plot} - \text{Yield in control}) \times 100}{\text{Attainable yield (2500 kg)}}
\]

To test for the result of combining mineral and organic fertilizers, the interaction effects (added yields from combining fertilizer types) on grain yield was determined according to Vanlauwe et al. (2002):

\[
\text{Interactive effect} = Y_{\text{comb}} - (Y_{\text{fert}} + Y_{\text{con}}) - (Y_{\text{OM}} + Y_{\text{con}}) - Y_{\text{con}}
\]

where \(Y_{\text{con}}\), \(Y_{\text{fert}}\), \(Y_{\text{OM}}\) and \(Y_{\text{comb}}\) signify mean grain yields in the control, treatments with sole application of inorganic fertilizer, organic fertilizer, and in the treatment receiving both inorganic and inorganic fertilizers, respectively. In Equation 2, yields are adjusted for similar amounts of organic resources and mineral N and P applied in the combined as in the sole treatments. Sample test was used to determine statistical significance of interactive effects from combining fertilizers. Positive interactive effect signifies the additional yield obtained through the combined application of mineral and organic fertilizers compared with what is obtained when either input is applied on its own at the same total rate in the combined application.

### RESULTS

**Mineral N, P and organic fertilizers on common bean grain yield and their relative responses**

On all the three soils, there were significant (P<0.05) yield differences observed with manure application (Table 3). Bean yield was improved over the non-manured controls on all soil types. However, increasing manure application from 2.5 to 5.0 t ha\(^{-1}\) did not improve yield. It is noteworthy that common bean had greater yields on Phaeozem and Umbrisol soils compared with Cambisol regardless of manure application.

The greatest relative yield increases on Phaeozem soil occurred when nutrient applications included both mineral N and P fertilizers and manure, particularly when 5 t ha\(^{-1}\) manure applications were used with mineral fertilizers (Table 4). On Cambisol soil, application of mineral N and P fertilizers without manure largely did not improve yield (Table 5). The application of manure with mineral N and P resulted in similar relative yield increases as on Phaeozem. The greatest relative (added yield) yield for mineral fertilizers without manure was a 3.4% increase, considerably less than 17.4 and 24.8% found when 2.5 and 5.0 t ha\(^{-1}\) manure were included with mineral N and/or P (Table 5). Manure at 5.0 t ha\(^{-1}\) increased common bean yield by 11.9% in the absence of mineral fertilizers. On Umbrisol soils, fertilizer application significantly (p < 0.05) increased common bean yield (Table 6). Yield response to mineral fertilization N and P addition on Umbrisol was always positive, but not

### Table 3. Effect of manure application on bean yield (kg ha\(^{-1}\)) on three soil types.

| Manure (t ha\(^{-1}\)) | Phaeozem | Cambisol | Umbrisol |
|------------------------|----------|----------|----------|
| 0.0                    | 1836     | 1370     | 1824     |
| 2.5                    | 2063     | 1609     | 1975     |
| 5.0                    | 2099     | 1719     | 2040     |
| PsF                    | 0.006    | <0.001   | 0.018    |
| LSD (0.05)             | 169      | 170      | 151      |

Fisher's protected Least Significant Differences (LSD) at 0.05 probability level was used to separate means when significant differences were evident.
Table 4. Relative yield change (R) due to fertilizer application on Phaeozem.

| N (kg ha⁻¹) | P (kg ha⁻¹) | Manure (t/ha) | 0.0 | 2.5 | 5.0 |
|-------------|-------------|---------------|-----|-----|-----|
|             |             | Grain (kg ha⁻¹) R (kg ha⁻¹) | Grain (kg ha⁻¹) R (kg ha⁻¹) | Grain (kg ha⁻¹) R (kg ha⁻¹) |
| 0           | 0           | 1519          - | 1800 | 281 (12.8) | 1631 | 111 (5.1) |
| 0           | 7.5         | 1584          65 (3.0)* | 1589 | 69 (3.2) | 1746 | 226 (10.3) |
| 0           | 15          | 1792          273 (12.5) | 1849 | 330 (15.1) | 1826 | 306 (14.0) |
| 7.5         | 7.5         | 1594          74 (3.4) | 1859 | 339 (15.5) | 1958 | 438 (20.0) |
| 7.5         | 15          | 1621          101 (4.6) | 1912 | 393 (18.0) | 1928 | 408 (18.7) |
| 15          | 7.5         | 1603          84 (3.8) | 1712 | 193 (8.8) | 1940 | 421 (19.2) |
| 15          | 15          | 1540          21 (1.0) | 1886 | 366 (16.7) | 1646 | 126 (5.8)  |
| LSD (0.05)  | -           | -             | -   | -   | -   |

*Figures in parenthesis are relative yield change (%) resulting from fertilizers application.

Table 5. Relative yield change (R) due to fertilizer application on Cambisol soil.

| N (kg ha⁻¹) | P (kg ha⁻¹) | Manure (t ha⁻¹) | 0.0 | 2.5 | 5.0 |
|-------------|-------------|----------------|-----|-----|-----|
|             |             | Grain (kg ha⁻¹) R (kg ha⁻¹) | Grain (kg ha⁻¹) R (kg ha⁻¹) | Grain (kg ha⁻¹) R (kg ha⁻¹) |
| 0           | 7.5         | 1228           - | 1319 | 91 (4.2) | 1487 | 260 (11.9) |
| 0           | 15          | 1101           -126 (-5.8)* | 1609 | 381 (17.4) | 1489 | 261 (12.0) |
| 15          | 7.5         | 1080           -148 (-6.8) | 1441 | 213 (9.7) | 1581 | 353 (16.1) |
| 15          | 15          | 1299           71 (3.3) | 1450 | 223 (10.2) | 1605 | 377 (17.2) |
| 7.5         | 7.5         | 1171           -57 (-2.6) | 1256 | 28 (1.3) | 1485 | 258 (11.8) |
| 15          | 7.5         | 1303           75 (3.4) | 1348 | 121 (5.5) | 1408 | 180 (8.2)  |
| 15          | 15          | 1133           -95 (-4.3) | 1160 | -67 (-3.1) | 1770 | 542 (24.8) |
| LSD (0.05)  | -           | -             | -   | -   | -   |

*Figures in parenthesis are relative yield change (%) resulting from fertilizers applications.

particularly consistent. Typically, the larger yield increases occurred only with the inclusion of manure. However, application of 7.5 kg P ha⁻¹ or 15 kg N ha⁻¹ had large increases in yield despite the absence of manure. Although the generally greater yield increases with combined N and P fertilizer application, the greatest yield increase on Umbrisol soil, 36%, occurred with 5.0 t manure ha⁻¹ and no mineral N or P. This added relative yield was 10% greater in comparison to manure applied with N and or P best combinations of (7.5N + 15P) 2.5 and (15N+15P) 5.0 t ha⁻¹.

Interactive effect between mineral N and P and organic fertilizer

Generally, combining chicken manure with mineral N and/or P fertilizers did not necessarily result in larger yield benefits (synergistic effect) than either of mineral and organic fertilizers separately applied at the same
Table 6. Relative yield change (R) due to fertilizer application on Umbrisol soil.

| N (kg ha$^{-1}$) | P (kg ha$^{-1}$) |    | Manure (t ha$^{-1}$) |    |    |
|------------------|------------------|----|----------------------|----|----|
|                  |                  |    | 0.0                  | 2.5| 5.0|
|                  |                  |    | Grain (kg ha$^{-1}$) | R (kg ha$^{-1}$) | Grain (kg ha$^{-1}$) | R (kg ha$^{-1}$) | Grain (kg ha$^{-1}$) | R (kg ha$^{-1}$) |
| 0                | 0                | 1397 | -                  | 1731 | 334 (15.3) | 2183 | 787 (36.0) |
| 7.5              | 0                | 1857 | 461 (21.1)*        | 1703 | 306 (14.0) | 1758 | 362 (16.5) |
| 15               | 7.5              | 1469 | 73 (3.3)           | 1648 | 251 (11.5) | 1760 | 364 (16.6) |
| 7.5              | 0                | 1628 | 231 (10.6)         | 1607 | 210 (9.6)  | 1669 | 272 (12.4) |
| 7.5              | 15               | 1492 | 95 (4.3)           | 1950 | 554 (25.3) | 1613 | 216 (9.9)  |
| 15               | 7.5              | 1851 | 454 (20.8)         | 1908 | 511 (23.4) | 1760 | 363 (16.6) |
| 15               | 15               | 1734 | 337 (15.4)         | 1720 | 324 (14.8) | 1570 | 174 (7.9)  |

LSD (0.05) - 396 

*Figures in parenthesis are relative yield change (%) resulting from fertilizers applications.

Table 7. Additive (extra) yield benefits from combining organic with mineral N and P fertilizers on three diverse soils.

| N (kg ha$^{-1}$) | P (kg ha$^{-1}$) | Phaeozem | Cambisol | Umbrisol |
|------------------|------------------|----------|----------|----------|
|                  |                  | 2.5 t | 5.0 t | 2.5 t | 5.0 t | 2.5 t | 5.0 t |
| 0                | 0                | 2.5 t | 5.0 t | 2.5 t | 5.0 t | 2.5 t | 5.0 t |
|                  | 7.5              | -276  | 51    | 417    | 128   | -488  | -886  |
|                  | 15               | -224  | -78   | 270    | 242   | -156  | -495  |
|                  | 0                | -16   | 253   | 60     | 46    | -355  | -746  |
| 7.5              | 7.5              | 11    | 196   | -7     | 54    | -53   | -462  |
|                  | 15               | 28    | 255   | -46    | -155  | 124   | -665  |
| 15               | 0                | -154  | 175   | -64    | 378   | -277  | -1067 |
|                  | 7.5              | -172  | 226   | 214    | -41   | -347  | -760  |
|                  | 15               | 65    | -5    | 220    | -237  | -264  | -299  |

LSD (0.05) - 777  715  960

rate. The interaction effect was mainly positive on Phaeozem and Cambisol. On Phaeozem interactive effect was greater with mineral fertilizer combination at 5.0 t than at 2.5 t manure ha$^{-1}$ (Table 7). Adding N increased interactive effect from negative to positive at increasing P rate at the 7.5N. On Cambisol, the interaction effect was mainly positive and higher at 2.5 than 5.0 t manure with mineral fertilizers. On Umbrisol, the interaction effect was only positive (142 kg) for 7.5N +15P at 2.5 t manure ha$^{-1}$.

DISCUSSION

Mineral N, P and organic fertilizers on grain yield and relative responses of common beans

Common bean grain yield response to improved mineral and organic fertilizer use is specific to soil types, nutrient limitations and inputs. Manure application significantly increased yield over the control despite of no yield difference between 2.5 and 5.0 t manure ha$^{-1}$. These yields are less than the yield potential of K131 variety. This could be due to the Leibig’s law of the minimum caused by major nutrients in the applied fertilizer (Table 2). Large amounts of N and P from manure are often in organic forms and poorly available for uptake by young, growing plants when they are most sensitive to deficiencies (Rodriguez and Fraga, 1999; Fageria, 2014), thus, increasing risk when manure is the only applied source of nutrients. In conformity, the rate of yield increase with manure rates was greater on less fertile Cambisol than Phaeozem and Umbrisol soils (Table 3). This is confirmed by Sileshi et al. (2016) who observed low plant available nutrients and use efficiencies due to
poor nutrient ratios at high manure rates applied on more fertile soils. Manure recommendations should therefore be based on limiting nutrients, manure nutrient ratios and soil type fertility than rates.

Applying mineral N and P fertilizers improved common bean yields only a nominal amount on Phaeozem and Umbrisol soils, but generally decreased yields on Cambisol soil. Thus a coining by farmers ‘mineral fertilizers damage the soil (Vanlauwe and Giller, 2006)’ provided individual plot soil measurements’ variations are small and apparent with entire site composited sample (Rocha et al., 2017). Mineral fertilizer nutrient uptake in the tropics is highly influenced by SOC. The SOC concentration of these soils (Table 1) is below critical levels even for bean grain yield response to mineral fertilizers (Schwartz and Pastor-Corales, 1989; Wortmann et al., 1998; Okalebo et al., 2002; Musinguzi et al. 2016) making it risky for application on Cambisols. Goetttsch et al. (2016) reported that utilization of mineral fertilizers was economically advantageous on Phaeozem soil. Conversely, Goetttsch et al. (2017) reported an economic loss from fertilization of common bean on degraded Cambisol. Thus, the low yield of mineral N and P fertilizers suggests that their use should be specific to soils OC levels.

Furthermore, when mineral N and P applications were combined with manure, common bean yield was always enhanced. Surprisingly, yields at 5.0 t ha⁻¹ manure were greater than for mineral or combined fertilizers on Umbrisol as similarly reported by Mucheru-Muna et al. (2013). Combining fertilizers increases manure mineralization, improving nutrient remobilization and release. Manure also contains a large number of elements required for plant growth that are infrequently examined for yield enhancement in sub-Saharan Africa, particularly in common bean production systems. Some of the manure containing nutrients like Ca and Mg are in limestone, a major soil pH resulted in improvement recommendation (Kymuhendo et al., 2020). However, liming is uneconomical on Cambisol due to the high cost of limestone (Goetttsch et al., 2017) even when costs are accounted for over two rainy seasons, despite substantial yield increases. In the present study, bean yields were studied only in the season when fertilizers and manure were added. In acidic soils with substantial concentrations of extractable Fe²⁺ and Al³⁺, Mehlich-3 extractable P can be rapidly complexed and become unavailable for subsequent crops (Jones, 1998). Thus, residual effects can be substantial for high rates of P and manure application.

The bases in the manure like limestone enhance plant nutrition and productivity by improving many soils properties to release essential nutrients (Oustani et al., 2015). Nutrients in manure have not received adequate research attention in many developing countries to understand well their temporal variability due to the

influences of animal type and class, diet and storage conditions (Sileshi et al., 2016). However, chicken production has increased in recent years in several countries including Uganda (UBOS, 2015) and manure is more readily available for purchase than limestone. Still, long-term studies are necessary on degraded Cambisol and Umbrisol soils to better understand the residual and economic impacts of manure and limestone application even on subsequent crop production.

Additional yields due to fertilizers (Tables 4 to 6) require applying organic with N and P inorganic fertilizers with higher beneficial returns. Satyanarayan et al. (2002) observed unenhanced beneficial effects at higher rates of organic with mineral fertilizers. Also higher manure application rates are less accessible or affordable and may discourage usage. Primarily, if benefits are longer term, farmers are likely only to use these inputs on land that they own (Amede and Kirkby, 2004) and forego their use on rented or borrowed lands. Applications of comparatively small amounts of N and P (7.5 to 15 kg ha⁻¹) generally enhanced common bean yield in this study and is a promising method even for smallholder farmers (Goetttsch et al., 2016, 2017). From the current study, it appears that combining mineral N and P fertilizers with manure at 7.5 kg N + 15 kg P + 2.5 t manure ha⁻¹ on Umbrisol, 7.5 kg N and P ha⁻¹ + 2.5 t manure ha⁻¹ on Phaeozem and 15 kg N and P ha⁻¹ + 2.5 t manure ha⁻¹ on Cambisol soil could improve technology buy-in for higher yields. Depending on farmer resources and yield targets, relative yields increases would benefit farmers’ decisions based on soil type. Additionally, more studies are necessary on residual effect and to determine economically beneficial fertilizer rates for the shorter-and longer-term.

**Interactive yield effect of combined application of organic and mineral N and P fertilizers**

Although combining fertilizers resulted in larger yield benefits, positive yield interactions varied among soils (Table 7). Positive interaction is partly attributed to temporary immobilization of nutrients early in the season, so that they are protected from losses for later crop uptake. Affecting immobilization depends upon manure quality and soil characteristics like clay amount (Pincus et al., 2016). Materials like maize stover with moderate organic carbon have always produced positive interactive effect unlike high quality materials most especially for longer duration crops (Chivenge et al., 2009). The high quality manure used for this study would have led to excessive nutrient losses under some fertilizer combinations especially on Umbrisol and Phaeozem containing low clay concentrations. Nutrient fixation on clay surface may reduce further losses hence utilization and positive interactions on Phaeozem at 5.0 t ha⁻¹
manure. Meanwhile, higher clay concentration of Cambisol (Table 1) may have released more of the clay-fixed nutrients, during critical growth stages when BNF is low. Common beans are among the poorest symbiotic N$_2$ fixing legume (Kabahuma, 2013; Gunnabo et al., 2019) and often cease N$_2$ fixation during reproductive phases hence utilizing nutrients on the clay surface. Lack of beneficial returns to specific organic and mineral fertilizer combinations may make and encourage sole applications mainly those with positive relative increases (Tables 4 to 6) better options for farmers use. Separate fertilizer application may encourage fertilizer use on a larger area (extensive) as opposed to intensifications of the combination on a plot. Applying combinations with higher yields and some positive additive benefits would reduce risks like those associated with farmers’ habitual use of untested fertilizer combinations. Similarly, higher rates, mostly for manure applied with mineral fertilizers may discourage their usage even with positive yield interactions since farmers desire strong benefits of fertilizer integration. Moderate positive interactions may improve farmers’ perception on fertilizer integration, and hence adoption. In this respect, Jinwei and Lianren (2011) recommended application of small amount of inorganic fertilizers with organic materials but Tarfa et al. (2017) observed higher profit potential only if a minor amount of manure was added to mineral fertilizer. Therefore, application of above suggested low manure rates with N and P mineral fertilizers with positive interactions can be further field validated to avoid risky options.

Conclusions

Mineral and organic fertilizer use for improved soil fertility management in common bean farming systems should be specific to soil type, nutrient limitations and inputs. Greater bean grain yields were obtained on Phaeozem and Umbrisol soils compared to Cambisol soils. Larger relative yield increases occurred when nutrient applications included both mineral N and P fertilizers and manure particularly when 5 t ha$^{-1}$ manure applications were used with mineral fertilizers on more fertile soils. Application of mineral N and P fertilizers without manure largely decreased yield on Cambisol while on Umbrisol soil the response was always positive, but not particularly consistent and hence a risky intervention on degraded soils. The highest 36% added relative yield increase occurred on Umbrisol soil with the application of 5.0 t manure ha$^{-1}$ and no mineral N or P. However, higher yields from combining mineral N and P fertilizers with chicken manure did not necessarily result into a positive interaction effect. Also, the high quality manure resulted into negative yield interaction under some fertilizer combinations especially on Umbrisol and Phaeozem soils with characteristically lower clay concentrations. Primarily, any soil specific applications of chicken manure with N and P mineral fertilizers of this study require further field and economic validation so as to avoid risky options.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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