Evaluation of farm-level impacts of soil fertility management strategies in maize-bean farming systems in Uganda and Tanzania
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Abstract

We conducted an ex ante evaluation of soil fertility management strategies on soil organic matter (SOM), nitrogen balance, greenhouse gas (GHG) emissions, and profitability under three important scenarios: (1) inorganic fertilizers, (2) organic manure, and (3) combined organic manure and inorganic fertilizers. Focus group discussions and household surveys were used to collect data in Rakai, Uganda, and Lushoto, Tanzania. We assessed impact for three farm types (small scale, medium scale, and large scale) using a bio-economic model: FarmDESIGN. Our main findings are as follows. First, whereas in Lushoto the combined use of organic manure and inorganic fertilizers contributed the most to SOM relative to the baseline for all farm types, in Rakai the same scenario had greater impacts for only medium- and large-scale farms. For small-scale farms, improvement in SOM mostly came from the use of inorganic fertilizers. Second, in both countries, nitrogen balance increased across all scenarios and farm types. Third, the increase in SOM and nitrogen balance was accompanied by an increase in GHG emissions, especially for scenarios with manure or combining manure and inorganic fertilizers. Fourth, impacts were mixed in terms of profitability. In Lushoto, Tanzania, the small-scale farm has the lowest operating profit, while the large-scale farm has the highest. In Rakai, Uganda, gross margins from crops contributed the largest share to farm profitability.

Our findings not only suggest increased soil fertility with the adoption of improved management strategies but also highlight potential trade-offs in terms of increased emissions and reduced profitability for some farm types. Taking into account both synergies and trade-offs when promoting soil fertility management strategies might yield successful efforts.

Definition of terms

To enhance proper understanding of this report for all specialists across various disciplines and for non-specialists, we provide definition of some technical terms that have been used in this report.

Soil organic matter (SOM)
This refers to the organic component of the soil less than 2 mm in size, including tissues from plants and animals at various stages of decomposition. Undecomposed plant and animal tissues more than 2 mm in size are not considered part of SOM.

Soil organic carbon (SOC)
This is the main component of SOM forming 58% of its mass on average. Normally, soil carbon occurs in soil in two forms, organic and inorganic, i.e., oxidized and non-oxidized carbon. The sum of the two is equivalent to total carbon. Inorganic carbon occurs as minerals and salts from weathered rocks and sediments.

Profitability
This is the difference between total farm revenue and variable costs. Profitability in this case is measured as gross margins, hence fixed costs are not considered.

Nitrogen balance
This is the difference between nitrogen added to an agricultural system and nitrogen removed from the system per hectare of agricultural land.

Feed balance
This refers to the comparison of the amount of feed demanded by livestock on a farm and the utilizable amount of feed available. It is normally used to determine livestock carrying capacity of a particular farm or even region.
**Introduction**

The adverse impacts of climate change on agriculture will exacerbate the development challenges of ensuring food and nutrition security, and supporting livelihoods, particularly in sub-Saharan Africa (SSA) (FAO, 2016). Many countries in SSA are vulnerable to climate variability and change, in part because of their high dependence on rainfed agriculture and lack of or inadequate adaptive capacity (Millner and Dietz, 2015). Most of SSA is projected to see a decrease in crop season length and an increase in probability of season failure with negative impacts on food availability, especially in rainfed systems (Lobell et al., 2008; Schlenker and Lobell, 2010; Thornton et al., 2014).

Maize (*Zea mays*) and dry beans (*Phaseolus vulgaris*) rank as the most important food crops in East Africa, with an overall monetary value of US$1.2 billion for common beans and US$8.2 billion for maize (FAO, 2016). Statistics from FAOSTAT (Table 1) show that, in 2014, Tanzania – the leading producer of beans in East Africa – produced 1.1 million tons of beans occupying 1.1 million hectares of land. In the same year, Uganda produced 876,576 tons of the crop occupying 674,000 hectares of land and corresponding to 87% of the total pulse area harvested in the country. Maize production was 6.7 million tons in Tanzania and 2.7 million tons in Uganda, representing close to two-thirds of the total cereal area harvested in both countries.

**Table 1** Production of dry beans and maize in Uganda and Tanzania

<table>
<thead>
<tr>
<th>COUNTRY</th>
<th>DRY BEAN PRODUCTION (TONS)</th>
<th>CROP AREA HARVESTED (HA; PROPORTION OF TOTAL PULSE AREA HARVESTED, %)</th>
<th>MAIZE PRODUCTION (TONS)</th>
<th>CROP AREA HARVESTED (HA; PROPORTION OF TOTAL CEREAL AREA HARVESTED, %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tanzania</td>
<td>1,114,500</td>
<td>1,134,394; 55%</td>
<td>6,737,197</td>
<td>4,146,000; 64%</td>
</tr>
<tr>
<td>Uganda</td>
<td>876,576</td>
<td>674,000; 87%</td>
<td>2,763,000</td>
<td>1,105,000; 63%</td>
</tr>
</tbody>
</table>

Source: FAOSTAT data for 2014.
Rising temperature and irregular rainfall patterns are projected to decrease yields for maize and beans in both Tanzania and Uganda (Thornton et al., 2010). In addition, several factors, including poor access to input, output, and credit markets; unavailability of quality inputs and limited knowledge on their application; and poor land health, contribute to the low productivity in SSA (Cairns et al., 2013; Mwongera et al., 2014a, 2014b; Bold et al., 2017). Soil fertility depletion is recognized as an important biophysical factor that limits smallholder agricultural productivity across SSA (Sanchez et al., 1997). The benefits of using organic manure and mineral fertilizers for soil fertility have been continually shown (Palm et al., 1997; Place et al., 2003). Although undoubtedly insightful, most of the previous research has focused more on the yield benefits associated with soil fertility management strategies while less attention has been paid to understanding the potential trade-offs and farm-level impacts from implementing such strategies.

In this study, we conducted an ex ante evaluation of the farm-level impacts of soil fertility management strategies (organic manure, inorganic fertilizers, and a combination of both) in maize–bean farming systems in Tanzania and Uganda. The specific objectives were to (i) characterize farming systems under current and improved soil fertility management, and (ii) assess the trade-offs and synergies of adopting a farming system with improved soil management strategies. We considered several environmental and economic indicators: crop area, feed balances, soil organic matter (SOM) balance, profitability, greenhouse gas (GHG) emissions, and nutrient cycles.

### Methodology

#### Data collection and identification of farm typologies

Focus group discussions were held with farmers in Lushoto, Tanzania, and Rakai, Uganda, to identify the major farm types in the region. In both countries, the farms were characterized mostly based on amount of land owned and household income. Selection of these variables was informed by recent literature that uses similar characterization (see, for example, Chikowo et al., 2014; Mwongera et al., 2017). Three main farm typologies were identified.

The first typology was small-scale farms. These farms are characterized by very little or no ownership of livestock, use of local seeds for crops, and use of poor (rudimentary) farming techniques. Households in this category often borrow farm implements from neighbors and supply their labor for off-farm income.

The second type of farms we identified was medium-scale farms. These households rely on own family labor for farming activities; they mostly use local seeds, saved from previous seasons, and they use manure for fertilization. In addition, they practice both intercropping and mixed cropping and own some livestock, which is either tethered or zero-grazed.

The third typology is large-scale farms, which practice monocropping rather than mixed cropping and mostly use improved seeds. In addition, such households apply fertilizer, keep improved breeds of livestock, and mechanize their farming activities.

We further carried out field visits in Lushoto and Rakai in July and August 2015, respectively. Three villages were visited at each site: Boheloi, Yamba, and Mbuzii in Lushoto, and Gosola, Kyengeza, and Kijjuna in Rakai. In each village, three farms representative of the three farm types were identified. Additional household survey data were obtained from the CCAFS IMPACTlite survey. The survey collected detailed data on, among other aspects, crop and livestock production and management. The collected data were used in the modeling of impacts of soil fertility improvement strategies as described below.

### Ex ante modeling of the impacts of soil fertility improvement strategies

Ex ante modeling of the impacts of soil fertility management strategies was performed using the FarmDESIGN model. FarmDESIGN was developed for the evaluation of relations between various farm performance indicators and the consequences of adjustments in farm management. The model couples a bio-economical farm model that evaluates the productive, economic, and environmental farm performance with a multi-objective optimization algorithm that generates a large set of Pareto-optimal alternative farm configurations (Groot et al., 2012). Using this model, we therefore describe and explain the outcomes of the current (baseline) configuration of selected farms and explore alternative farm configurations (scenarios). FarmDESIGN supports the evaluation and re-design of mixed farming systems (Groot et al., 2012). The user follows a learning cycle

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1. CCAFS stands for the CGIAR Research Program on Climate Change, Agriculture, and Food Security. IMPACTlite Survey Dataset - doi:10.7910/DVN/24751
according to the Describe, Explain, Explore, and Design (DEED) concept (Tittonell, 2008). The farm is described by its farming system components and their biological and economic characteristics.

To facilitate further analysis, we constructed three scenarios that were evaluated against a baseline scenario. The three scenarios correspond to switching to an alternative production system with different soil fertility management strategies: (i) organic fertilizer, (ii) inorganic fertilizer, and (iii) combination of organic and inorganic fertilizer. All three scenarios included the use of improved maize (H. Obregon and FM 6) and dry bean (Canadian Wonder and Calima) varieties. Yields for maize and dry beans were obtained from simulations using the Decision Support System for Agrotechnology Transfer (DSSAT) model. The main objective of simulating different yield domains was to compare a typical farmer’s crop management under spatial variations of biophysical conditions offered by the DSSAT model, including change of cultivars, different planting date windows, and amount of applied inorganic or organic fertilizer. The yields that were modeled in DSSAT are presented in Table 2. They are based on the site and the planting season. If the particular farm did not currently grow one of the crops in a specific season, then this crop was omitted for that season. Below we describe the scenarios, starting with the baseline.

### Table 2  Maize and bean yields (kg/ha) obtained in DSSAT modeling

<table>
<thead>
<tr>
<th>CROP</th>
<th>SEASON</th>
<th>FERTILIZER TREATMENT (T/HA)</th>
<th>MANURE TREATMENT (T/HA)</th>
<th>FERTILIZER AND MANURE TREATMENT (T/HA)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Panel A: Lushoto, Tanzania</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maize</td>
<td>1st season</td>
<td>3.90</td>
<td>3.61</td>
<td>4.63</td>
</tr>
<tr>
<td></td>
<td>2nd season</td>
<td>1.62</td>
<td>1.60</td>
<td>1.88</td>
</tr>
<tr>
<td>Beans</td>
<td>1st season</td>
<td>0.89</td>
<td>0.82</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>2nd season</td>
<td>0.49</td>
<td>0.46</td>
<td>0.51</td>
</tr>
<tr>
<td><strong>Panel B: Rakai, Uganda</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maize</td>
<td>1st season</td>
<td>3.21</td>
<td>2.59</td>
<td>4.07</td>
</tr>
<tr>
<td></td>
<td>2nd season</td>
<td>2.88</td>
<td>2.26</td>
<td>3.58</td>
</tr>
<tr>
<td>Beans</td>
<td>1st season</td>
<td>0.77</td>
<td>0.67</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>2nd season</td>
<td>0.55</td>
<td>0.48</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Source: Authors’ own calculations using the Decision Support System for Agrotechnology Transfer (DSSAT) model.

**Description of scenarios**

**(a) Scenario 1: Baseline scenario**

This scenario considers the farmer’s current farming system or base production system for each of the three farm types as described below in the section on characterization of farming system typologies.

**(b) Scenario 2: Fertilizer**

This scenario includes the use of inorganic fertilizer. For beans, we consider the application of 125 kg/ha of DAP (16-46-0) at planting date. For maize, we consider the application of 50 kg/ha of DAP (16-46-0) at planting date and 50 kg/ha of urea 45 days after planting date.

**(c) Scenario 3: Manure**

In this scenario, we consider the use of animal manure for fertilization. Specifically, we assume the application of 2 t/ha of organic fertilizer (manure) 15 days before planting. In addition, the scenario includes the use of 1.5 t/ha of mulch (in the form of crop residues).

**(d) Scenario 4: Combined manure plus fertilizer**

The final scenario that we considered combined scenario 2 and scenario 3 as described above. This scenario, therefore, involved a combination of inorganic fertilizer and organic manure.
Results

Characterization of farming system typologies

Small-scale farms
In Lushoto, Tanzania, the small-scale farm in Boheloi Village is 1.3 hectares large, and maize is the main crop cultivated. Other crops on the farm include green gram, banana, beans, cassava, and tomatoes. In addition, green pepper is grown in the dry season. In terms of fodder, Guatemala and Napier grasses are grown along the boundaries of the farm. The above-mentioned crops are mainly cultivated for household consumption, except beans and tomatoes, which are mostly for sale. Maize bran is processed from maize grain husks and used for livestock feed. All the maize stover as well as bean and banana crop residues are fed to livestock. Maize stover and bean crop residues are fed to livestock in the rainy season, whereas banana residues are used as livestock feed in the dry season. Residues from the rest of the crops are all left on the field as mulch. Labor for cropping and livestock activities is provided by household members only. There are three improved cattle and three chickens on the farm. During lactation, the farmer can collect up to 2 kilograms of milk per day, 50% of which is sold and the rest is for household consumption. The chickens feed on maize bran from the farm during the wet season and purchased feed during the dry season. Napier and Guatemala grasses grown around the farm form the largest portion of the feed basket for the cattle during both seasons, although more residues are fed during the dry season than during the wet season. The cattle are fed through zero grazing throughout the year and the chickens are housed in a roofed enclosure for 14 hours and range free the rest of the time. All the manure collected is applied on crop fields. There is no off-farm income.

In Rakai, Uganda, the small-scale farm in Kijjuna Village is less than 1 hectare in size and is divided into two plots. Maize and coffee are the main cultivated crops, which are intercropped with plantain, beans, or cassava. Cassava, plantain, and beans are mainly used for household consumption. Beans are also saved for seed during both the long (March to June) and short (August to November) rainy seasons, whereas coffee and some of the maize are sold during both seasons. All of the residue is left on the crop fields as mulch except cassava stalks, which are used as fuel. Household members provide labor for the cropping activities.

Medium-scale farms
The medium-scale farm in Mbuzi Village, Lushoto, Tanzania, is about 5 hectares and maize is the main cultivated crop. Beans, Irish potatoes, tomatoes, and bananas are also grown on the farm. Beans are used for household consumption and sale, and some are kept as seed. Irish potatoes are grown entirely for household consumption. All the other crops are grown for both sale and household consumption. All the maize stalks, potato residue, and tomato residue are used as mulch in both the wet season and dry season. All the bean residue and maize stover are fed to livestock in the dry season but in the wet season most of the bean residue is used as mulch. Household members provide most of the labor for cropping and livestock activities although a few of the activities are carried out by hired casual labor (especially during planting and weeding). There are 12 chickens,
3 cows (one local and two improved), and 1 improved goat on the farm. At least one cow is sold per year for slaughter. About half of the amount of milk produced is sold while the rest is consumed at the household level. Most of the eggs are sold. The chickens are locked up during the rainy season and fed on maize bran all season. The cows and the goat are fed on maize stover, Napier grass, and maize bran. The cows and the goat are fed through zero grazing all year, and the chickens spend about half the time in a roofed enclosure and the rest of the time range free.

In Rakai (Kijjuna Village), Uganda, the medium-scale farm covers about 9 hectares and is divided into eight plots. Coffee and plantain are the main cultivated crops, although there are also maize, bean, and cassava intercrops. Most of the maize and beans are sold during both seasons. Plantain, on the other hand, is mostly used for household consumption. Coffee is produced solely for sale. At least a quarter of the maize and bean residue is fed to livestock during both seasons and the rest is left on the crop fields as mulch. Banana leaves and cassava peels are mostly used for livestock feed; only about a quarter of the stems are used for feed while very small amounts are used as mulch. All the cassava stalks are used as fuel and the coffee residues are mostly left on the field as mulch. There are 25 chickens, 8 local cattle, 3 local goats, and 1 pig. The animals are for both sale and household consumption. Eggs are mostly for household consumption; a few are left for hatching. Fifty percent of the cow milk obtained per day (2–3 kg) is for household consumption and the other half is for sale. The labor for cropping activities comes from both household members and a permanently employed worker. The largest percentage of the feed basket for the pig comprises maize bran and the rest comes from banana and cassava peels. Natural grasses form most of the cows’ and goats’ diets, whereby they graze for 9 hours on communal grazing land and spend the remaining hours in a non-roofed enclosure grazing on residue. The pig spends 24 hours in a non-roofed enclosure, which is where it feeds and sleeps. The chickens are housed in a roofed enclosure for 13 hours and released to range free for the rest of the time. All the manure collected is applied on the crop fields.

Large-scale farms
The large-scale farm in Lushoto (Yamba Village), Tanzania, is 3.6 hectares and maize is the main crop; other crops cultivated are bananas, spinach, beans, and coffee. Beans are the only crop that is grown in the second season (October to December); all the others are grown in the first season (March to June). Most of the harvest from crops is sold; the remaining amounts are split between household consumption and seed. Maize, bean, and plantain residue is all fed to livestock. Household members carry out cropping and livestock activities. The farm has two ducks, four cows, and four pigs. The farmer collects 5 kilograms (kg) of milk per day during the wet season and 3 kg during the dry season. On average, the household consumes 1 kg of milk per day all year round and the remaining amount is sold at US$0.24/kg. At least one cow is sold per year. The largest percentage of the feed basket for the cows comes from on-farm cut-and-carry grass during the wet season; the rest of the feed basket consists of purchased maize bran, maize stover, and bean straw. During the dry season, cut-and-carry grass forms half of the feed basket and the rest is crop residue and purchased maize bran. The pigs largely feed on maize bran. The cows and pigs spend 24 hours in a roofed enclosure throughout the year, whereas the ducks spend half the day in a roofed enclosure and the other half ranging free. All the manure collected is used on cropland.

In Rakai (Gosola Village), Uganda, the large-scale farm has 20 hectares. Maize is the main crop, which has been intercropped with beans, plantain, sweet potatoes, tomatoes, and coffee. Most of the crops are sold during both seasons and the rest are for household consumption. Some maize and beans are kept as seeds. All of the bean residue and tomato residue are left on the field as mulch. Most of the maize and sweet potato residue is left on the crop fields as mulch and half of the plantain residue is fed to the livestock and the rest is used as mulch. Most of the labor for crop and livestock activities is provided by household members and a hired farm worker. There are 40 chickens, 20 cattle, 30 goats, and 4 pigs. The goats, chicken meat, and eggs are for both household consumption and sale. The chickens spend 11 hours in roofed enclosures and the remaining hours ranging free. The pigs spend all day and night in a non-roofed enclosure and the cattle and goats spend 11 hours in a non-roofed enclosure, 1 hour grazing on crop residues on crop fields, and the remaining hours grazing off-farm. All the manure collected is used on crop fields.

Impact of soil fertility management strategies

Impact of baseline scenario
Across the three farms in Lushoto, soil organic matter (SOM) inputs come from crop stubble, crop residues, and on-farm manure (Figure 1). SOM outputs are in the form of degradation of the crop residues, stubble, and manure. At baseline, the model is parameterized for the balance to be zero. All farms are producing manure and applying it for fertilization. The medium-scale farm has
the highest proportion of crop stubble biomass, which is coming from the planted Napier grass. Grasses contribute more root biomass to the soil than annual crops.

Figure 1 Contributions to soil organic matter balance, Lushoto, Tanzania.

In Rakai, the small-scale farm has no livestock and is not importing any manure. Therefore, only crop stubble and residues left on the fields contribute to SOM (Figure 2). The other two farms have livestock. Inputs to the soil organic matter on the medium-scale farm are from both crops and livestock. On the large-scale farm, livestock manure produced on the farm is the largest contributing source of organic matter (more than 40%).

Figure 2 Contributions to soil organic matter balance, Rakai, Uganda.

In Tanzania, many transfers of nutrients, particularly nitrogen, occur between the different pools of nutrients on the farm (crops, soils, livestock, manure). However, the farm nitrogen balance considers nitrogen that is entering and leaving the farm boundaries indicating whether there is an overall loss of nitrogen or an accumulation of nitrogen at the farm level. The inputs considered are imported crop products (in the context of this study), imported manure and inorganic fertilizer, nitrogen fixation by leguminous crops, nonsymbiotic nitrogen fixation, and atmospheric deposition. The exports of nitrogen considered are from the export (sale) of livestock and crop products produced from the farm, and household consumption of farm products (livestock and crops), which leave the farm in the form of excreta.

The nitrogen balance (N balance) is 54 kg, 56 kg, and 20 kg N/ha for the small-scale, medium-scale, and large-scale farms, respectively. On the small-scale farm,
the N balance is high because of the “imported crops,” which represent the grasses from cut-and-carry that are collected outside the farm (Figure 3). As shown in Figure 3, all three farms in Lushoto are importing inorganic fertilizer, which is the most important contributor to the N balance for the medium- and large-scale farms. Sales and household consumption of crops are the largest sources of loss of N on the small farms. In terms of exports, crop sales are the most important sources for the medium- and large-scale farms (Figure 3).

In Uganda, the farm nitrogen balance is negative on the small-scale (-26 kg N/ha) and medium-scale (-6 kg N/ha) farms and positive on the large-scale farms (122 kg N/ha) (Figure 4). On all three farms, there are no inputs in the form of imported organic or inorganic fertilizer. The major form of imported nitrogen on the large-scale farm is in the form of imported crop products, which represent nitrogen collected by livestock while grazing off the farm. This explains the high positive balance on that farm. In terms of outputs, all farms were selling crops and some livestock products (medium-scale and large-scale farms). However, on both the small-scale and medium-scale farms, exports in the form of household excreta (from household consumption of farm products) were even greater than crop exports, thus contributing to the negative nitrogen balance.
Livestock are the largest contributor to GHG emissions on the three farms in Lushoto, Tanzania. At this study site, methane from enteric fermentation from ruminants and both methane and nitrous oxide from manure production, storage, and application were the bulk of the emissions (Figures 5 and 6). GHG emissions intensities reflect livestock density on the farms. Crop residues contribute very little to GHG emissions, and emissions from inorganic fertilizer are highest on the medium-scale farm since it has the highest applications rates.

Similarly, in Rakai, livestock were the main contributor to GHG emissions from enteric fermentation and manure production, storage, and application (except on the small-scale farm) (Figures 7 and 8). The small-scale farm had the lowest GHG emissions because of the lack of livestock and minimal use of inputs. Only nitrous oxide emissions from crop residues (as well as on the large-scale farm) were a source of GHG emissions.
In Lushoto, Tanzania, the small-scale farm has the lowest operating profit while the large-scale farm has the highest (Figure 9). All farms are consuming part of the farm production; the small-scale farm had the lowest net income, which was nearly half of the operating profit (Figure 9). On the small-scale and large-scale farms, crop production margins are contributing the most to the operating profit while on the medium-scale farm livestock and crop production contribute equally to operating profit (Figure 10).
In Rakai, Uganda, gross margins from crops contributed the largest share to farm profitability on all three farms (Figures 11 and 12). Livestock contributed little on the medium-scale farm and close to half of the profit on the large-scale farm. Profitability was much higher on these two farms than on the small-scale farm. The small-scale farm is less than 1 hectare and depends solely on crop production for income while the medium- and large-scale farms 9 and 20 hectares, respectively, have more land for crop production in addition to their livestock. However, once household consumption was deducted, the net income of all three farms fell. The lowest was on the small-scale farm (US$288), followed by the medium-scale farm (US$1050), and it was highest on the large-scale farm (US$1388). The difference between the farm profitability and net income was greatest on the medium-scale farm. This was due to the large share of household consumption.

**Figure 10** Contributions to baseline operating profit (%), Lushoto, Tanzania.

**Figure 11** Baseline operating profit and net income (USD/year), Rakai, Uganda.
Impact of fertilizer and manure scenarios
In Lushoto, in the scenarios with manure and the combination of manure and fertilizer, the soil organic balance increases more than with the scenario in which only inorganic fertilizer is applied (Figure 13). Because most farms could not produce enough manure to meet the recommended rate, off-farm purchased manure was required. As the contribution to SOM from manure increases, so does the degradation of manure output. Contributions to SOM from residues increase in all farm types compared with the baselines. We find that, as crop production increases, so does the quantity of crop residues.
In all three farm types and in all scenarios in Rakai, the SOM balance improved compared with the baselines (Figure 14). Compared with the manure only and inorganic fertilizer only scenarios, the combination scenario had the greatest impact in both the medium-scale and large-scale farm types in terms of SOM. This was because the yields had a better response and there was already an input from the farms’ own animal manure. On the small-scale farm, the inorganic fertilizer scenario contributed more to SOM balance than in the other scenarios. For small-scale farms, the crop response was more important than the manure alone, which adds a lot of crop stubble and residues for mulching.

**Figure 14** Contributions to SOM baselines and scenarios per farm type, Rakai (kg SOM/ha).

In Lushoto, N balance increased on the small-scale and large-scale farms across the three scenarios (Figure 15). On the medium-scale farm, the N balance did not increase, remaining close to the baseline level and decreasing in the manure scenario. This farm was already using inorganic fertilizer on the maize/beans and making a switch to application of manure did not compensate for the quantities of N provided by the inorganic fertilizer.

In most cases in Rakai, Uganda, the farm nitrogen balance increased across the different farm types and scenarios (Figure 16). On the small-scale farm, the scenarios with manure increased the balance the most, allowing for accumulation of nitrogen on the farm. On the medium-scale farm, the fertilizer scenario worsened the baseline negative balance. This is because as production increased even more crops were exported off the farm. This is also observed on the small-scale farm in the same scenario. Finally, on the large-scale farm, the N balance decreased from the baseline in the manure scenario. This was again because the increase in crop production that was sold was not compensated by the added input from manure. However, the balance was still positive (116 kg N/ha).
The addition of inputs to the soil will most likely result in an increase in GHG emissions. This was the case across the three farm types and three scenarios in Lushoto (Figure 17). There was an exception for the middle-scale farm, in the inorganic fertilizer scenario, with a small decrease in GHG emissions because the baseline fertilization was changed into a more efficient regime following recommended application rates. Increasing the amount of manure for fertilization in the manure scenario and in the combination scenario had the highest increases in GHG emissions across the three farms. The largest increase was for the large-scale farm since greater quantities needed to be added to fertilize all the fields. The total emissions from fertilizer and manure applied to the fields were equal to the emissions from enteric fermentation in those two scenarios.
In Rakai, Uganda, GHG emissions increased in all farm types and in all scenarios. This is because of the increased amount of N applied to the soil via the fertilizer and manure that released nitrous oxides (Figure 18). GHG emissions remained very low in all scenarios on the small-scale farm because of the absence of livestock. On the medium-scale and large-scale farms, the increases in GHG emissions throughout the scenarios were relatively unimportant because these scenarios do not affect the major source of GHG emissions, in this case livestock.

Figure 17  GHG emissions per farm baselines and scenarios, Lushoto, Tanzania.

Figure 18  GHG emissions per farm baselines and scenarios, Rakai, Uganda.
In Lushoto, the scenarios had a different impact on the profitability and net income of the farms (Figure 19). On the small-scale farm in the manure scenario, farm profitability decreased, while it increased in the inorganic fertilizer scenario. In the combination scenario, the profitability was slightly lower than that in the inorganic fertilizer scenario. On the medium-scale farm, the manure scenario drastically decreased farm profitability, while farm profitability increased a little in the inorganic fertilizer scenario. The profitability was at its lowest in the combination scenario. Finally, the profitability was most affected on the large-scale farm, especially in the scenarios in which manure was applied. Those resulted in negative profitability. The large-scale farm was most negatively affected by those scenarios because this farm was larger than the other two and most of it was cultivated with maize and/or beans; thus, large quantities of manure had to be purchased to meet the application rates described in the scenarios. Similarly, the medium-scale farm could not produce enough manure from its livestock.

Figure 19  Operating profit and net income baselines and scenarios per farm type, Lushoto (USD/year).

In Rakai, there was an increase in operating profit and net income across the farms and the different scenarios except on the large-scale farm for the manure and the fertilizer scenarios (Figure 20). In the latter case, an increase occurred in the operating profit but a small decrease occurred in the net income compared to the baseline.
Figure 20  Operating profit and net income baselines and scenarios per farm type, Rakai (USD/year).
Discussion

Through the participatory typology exercise carried out with farmers from the two sites, three farm typologies were identified. These were similar in terms of the defining variables (i.e., land size, livestock, and income) but not in their actual values or thresholds. Indeed, a large-scale farmer in Rakai could have as much land as 10 hectares and more, whereas, under the same type, in Lushoto a farmer could have 4 hectares. Although comparing the two sites was not the priority, it is interesting to note that some of the differences within each farm type at both sites could explain some of the different responses to the scenarios. The improved crop yields for maize and beans with the different fertilizer regimes served as input to the farm-scale model FarmDESIGN while other important farm characteristics were indirectly affected by these improved crop yields. For instance, higher crop production leads to an increase in residue production, which could then be fed to livestock, thus affecting livestock production (i.e., manure production).

Raising agricultural productivity and income for smallholder farmers to promote and achieve sustainable levels of food security is one of the three main objectives of climate-smart agriculture (Lipper et al., 2014). In this study, the increase in maize and bean production led to an increase in income from additional sales of those two crops, and income change was used as an indicator for increased productivity. In most cases, net income increased from greater yields of maize and beans in the various scenarios. Yet, this was not the case in Lushoto for the medium-scale and large-scale farms in the scenarios in which manure was applied. Because of the small herds of cattle in Lushoto, manure was required to be purchased to meet the recommendation rates for all the fields growing maize and/or beans. The cost of manure did not outweigh the revenues from the yields.

Resilience is another pillar of climate-smart agriculture. These scenarios affect resilience directly by improving soil fertility and by providing nutrients for the crops. In the short term, both technologies improved the N balance across the farms. Incorporating manure into soil is a direct way of increasing SOM. Inorganic fertilizer can also improve SOM indirectly. Following the recommended rates can increase the yields of maize and beans, thus providing more crop residues. These residues, if incorporated into the soil, can improve SOM. However, this practice was not always common on these farms because of competition for residues to be used as livestock feed. The small-scale farm in Rakai had no livestock and it was possible to increase SOM with only inorganic fertilizer.

The third pillar of climate-smart agriculture is mitigation. In this study, the application of manure, inorganic fertilizer, or both will translate into an increase in GHG emissions from the soil, from the release of nitrous oxide. However, it is important to note that, first on most farms, the largest contributor to farm GHG emissions is emissions from livestock production and primarily from enteric fermentation. This is commonly observed on East African smallholder farms (Seebauer, 2014). The farmer in Rakai from the small-scale farm has the lowest GHG emissions because he does not own any ruminants. As none of the technologies in this study targets livestock production directly, it is not surprising that not much
impact on GHG emissions is seen. Second, although there is no mitigation, the level of emissions on the farms is low, especially for those with low livestock densities ranging from 0.2 to 14 t/ha as baselines and almost doubling in some scenarios.

In this study, the new maize and bean varieties and the different fertilizer regimes were applied to all existing maize and bean fields on the farms. However, the heterogeneity of the farms was also visible in the fields with the variety of crops grown (not only maize and beans) and by the proportion in the fields. Hence, implications for implementing and scaling up the use of these varieties along with manure and/or inorganic fertilizer will depend on the scale of those crops on the individual farms. Large-scale fertilization of maize and/or beans with manure at 2000 kg/ha during both growing seasons will require the purchase of off-farm manure. As seen in the case of the medium-scale and large-scale farms in Lushoto, this was less economically profitable. It is neither likely nor sustainable to consider increasing the livestock herd to produce additional on-farm manure. Rotational application of manure at recommended rates should be prioritized, which would decrease the burden of purchasing manure. Other improved practices could be combined such as improving the collection and storage of manure. This would increase the quality of the manure and potentially decrease losses of nutrients and decrease GHG emissions (Herrero et al., 2013; Rufino et al., 2007).
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## Appendix

### Table 1  Average price per kg of fertilizer at local markets in USD.

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Note: 1 U.S. dollar was equivalent to 2183.20 Tanzanian shillings and 3367 Ugandan shillings.

### Table 2  Baseline and scenario N flows and balance at farm level in Lushoto (kg N/ha).

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Table 3  Baseline and scenario N flows and balance at farm level in Rakai (kg N/ha).

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