International Journal of Agricultural Sustainability

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tags20

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INTERNATIONAL JOURNAL OF AGRICULTURAL SUSTAINABILITY
2022, VOL. 20, NO. 5, 821–843
https://doi.org/10.1080/14735903.2021.1988478

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Manure matters: prospects for regional banana-livestock integration for sustainable intensification in South-West Uganda

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ABSTRACT

In South-West Uganda, manure is highly valued for sustaining yields of East African Highland Banana, but it is in short supply. As a result, banana growers import manure from rangelands up to 50 km away. We aimed to explore the potential of this regional banana-livestock integration to meet crop nutrient requirements for sustainable intensification of banana cropping systems. We used a mixed-methods approach supported by detailed data collection. Multiple spatial levels were integrated: field-level modelling to determine long-term nutrient requirements, a household-level survey to characterize farmer practices, and a regional-level spatial analysis to map banana production and manure source areas. For median to 90th percentile banana yields (37-52 t FW/ha/year), minimum K requirements were 118–228 kg/ha/year. To supply this with manure, 10.5–20.5 t DM manure/ha/year would be needed, requiring 47–91 tropical livestock units and 27–52 ha of rangeland, far more than what is potentially available currently. However, using only manure to satisfy potassium requirements increases the risk of N losses due to nutrient imbalances likely to result from large manure applications. For sustainable intensification, manure supplemented with K-based fertilizers is a better option than manure alone, as it is more cost-effective and reduces potential N losses.

KEYWORDS

East African highland banana; crop-livestock integration; potassium; spatial analysis; nutrient requirements; cattle

1. Introduction

South-West Uganda is a main production area for East African Highland banana (*Musa* spp. AAA-EA, hereafter referred to as 'banana'). The crop is sold to urban centres and used for home consumption (Wairegi & van Asten, 2010). Poor soil fertility is a major factor that constrains banana yields because of continuous production without sufficient addition of nutrients (Wairegi et al., 2010). In addition, Uganda's population growth rate is among the highest in the world (World Bank, 2020), resulting in an increasing demand for staple foods in combination with increasing land scarcity (Mwesigye et al., 2017). In South-West Uganda, agriculture is encroaching into forests and wetlands (Mugonola et al., 2013). Given these concerns and the importance of banana as both a staple food and cash crop, sustainable intensification of current banana cultivation in South-West Uganda is imperative. While sustainable intensification is a contested concept (Kuyper & Struik, 2014), we use the term to denote the need to produce more food from existing crop areas without further depleting natural resources, and while minimising potential negative environmental impacts (Garnett et al., 2013; Pretty et al., 2011). Banana farmers in the region consider the use of cattle manure the most important determinant of banana productivity, and extension services have for long stressed the importance of organic inputs to sustainably raise productivity. Since manure is in short supply in the

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cropping systems of Uganda (Jassogne et al., 2013), banana farmers import it from pastoral rangelands in trucks. Going beyond the farm or village level, crop-livestock integration occurs here at the regional level between two different agro-ecological zones.

The intensification of agriculture and the evolution of crop-livestock integration have often been placed in the context of Boserup's model, which states that population growth is the main trigger for intensification. With increasing population pressure, the value of land increases relative to the value of labour, and as a result farmers tend to switch to more labour- and capital-demanding cultivation practices that increase the returns to land (Baltenweck et al., 2003; Binswanger-Mkhize & Savastano, 2017). McIntire et al. (1992) postulate that crop-livestock interactions are minimal at very low population densities and increase with increasing population density because the positive interactions between crops and livestock – manure supply, animal traction, feed and fodder – allow farmers to intensify. With further population growth and intensification, farming systems are pushed towards specialization in production, thus reducing the potential for on-farm crop-livestock integration (Schut et al., 2021; Thornton & Herrero, 2015). If livestock farming remains largely grassland-based, manure becomes increasingly scarce for arable farmers, driving up manure prices. At this stage, mineral fertilizers often (partially) replace organic inputs (Baltenweck et al., 2003; McIntire et al., 1992; Schiere et al., 2002). However, the increased value of manure may also result in a transition towards regional integration by means of market-mediated interactions between crop farmers and livestock farmers (Thornton & Herrero, 2015). For specialization and regional integration to occur, adequate infrastructure and low transports costs are crucial to enable exchange of goods such as manure and feed (McIntire et al., 1992) and sales of produce in urban markets.

To understand the trajectories of crop-livestock integration, Sumberg (2003) conceptualized crop-livestock systems along four dimensions: space, time, management and ownership. This framework builds on the notion that mixed farming systems can be represented as a '*continuum of forms and levels of integration, [which] highlights the importance of specifying the nature, form and level of integration in terms of each dimension*' (Sumberg, 2003). The first dimension, space, is the most critical for manure exchange in African smallholder farming systems and highlights the importance of spatial proximity of crop and livestock production. In general, integration decreases with distance (Sumberg, 2003), although there are also large benefits from integration beyond farm level at higher spatial scales, such as at landscape, watershed or regional level (Lemaire et al., 2014; Ryschawy et al., 2017).

Research on banana productivity in Uganda has mostly focused on pest and disease management (Blomme et al., 2014; Rukazambuga et al., 1998), nutrients and mulching (Nyombi et al., 2010; Wairegi & van Asten, 2010), and drought (van Asten et al., 2011). The potential of banana-livestock integration has not been investigated, even though banana farmers regard manure to be essential for high yields and manure use is promoted by government extension services and scientists (Jassogne et al., 2013; Yamano, 2008). There is increasing recognition that crop-livestock integration (Lemaire et al., 2014; Ryschawy et al., 2017) and manure availability (Gowing et al., 2020) should be addressed at multiple scales, but assessments beyond the farm level are scarce. The crop-livestock integration currently taking place in South-West Uganda presents a unique case to investigate the potential for banana-livestock integration beyond the farm and village level. In this study, we use a mixed-methods approach and integrate multiple spatial levels with the objectives to:

(1) determine minimum long-term nutrient requirements through field level modelling
(2) characterize soil fertility management practices and crop-livestock integration through detailed fieldwork and household survey
(3) explore the prospects of this integration for the sustainable intensification of banana production
(4) identify the major factors determining these prospects based on the above theoretical frameworks describing intensification and integration processes.

2. Methodology

2.1. Study area

The study area is Isingiro district, South-West Uganda (Figure 1). Two sub-counties, Birere and Rugaaga, considered to be representative of the larger region, were selected. The population density is 289 and 190 persons/km^2 in Birere and Rugaaga, respectively, and agriculture is an important source of livelihood for over 80% of the working population (Isingiro

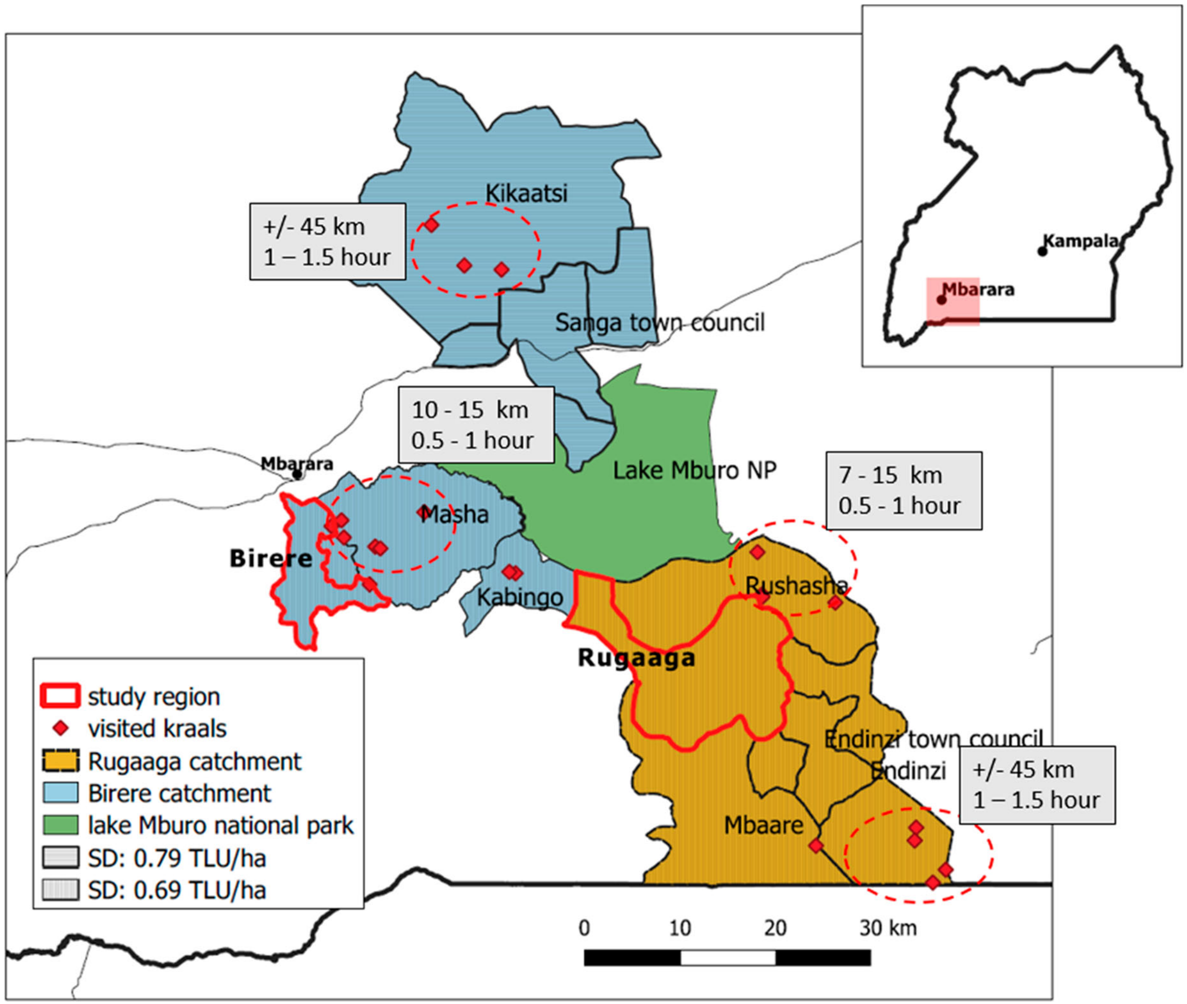

Figure 1. Map of the two selected banana-producing sub-counties and the area from which manure is imported (catchment). Text boxes indicate the approximate road distance and the travelling time from visited kraals (n = 20) to the respective banana-producing areas. SD: stocking density at the district level.

district local government, 2015). The elevation in both sub-counties lies between 1200 and 1700 m.a.s.l., with undulating hills of moderate to steep slopes, alternated with lower-lying valleys (in Birere) and higher plateaus (in Rugaaga). The dominant soils are Ferralsols, in combination with Acrisols in Birere, and with Nitisols in Rugaaga (Fischer et al., 2008). The valleys in Birere are relatively fertile due to deposition of material eroded from the steep hillslopes. In Birere, bananas are grown in the relatively fertile valleys and the less fertile undulating lowlands. In Rugaaga, banana production is mainly found on the relatively fertile plateaus. Average precipitation, is 1000 mm/year in Birere and 1300 mm/year in Rugaaga, both in bimodal distribution (CCKP, 2020), with a short dry season from December to February and a longer dry season from June to September. Banana is the main cash- and food- crop, mostly grown as a sole crop or with sparse maize and beans under the banana canopy.

2.2. Household survey

A farm survey on input use and soil fertility management practices was conducted from November 2019 to January 2020. During exploratory visits, farmers and key informants identified landscape position as one of the major determinants of input use for banana cultivation: valley plantations are perceived to be on more fertile soils and need less inputs, whereas plantations located at higher elevations need more inputs. To capture these patterns, random stratified sampling was done in four steps: (1) the banana area in the study region was mapped; (2) a digital elevation map of the banana area was downloaded; (3) three elevation strata were defined; and (4) households were sampled randomly within each of the three elevation strata.

The banana area in both sub-counties was mapped by overlaying Google satellite imagery with a grid of 500 × 500 m. Cells where banana covered more than 25% of the area were selected (Figure 2). Elevation maps and contour maps were constructed by downloading SRTM elevation data via the plug-in SRTM downloader in QGIS 3.4 Madeira. For each grid cell, elevation data for the central point was obtained. Subsequently, three elevation strata were defined in both sub-counties, based on the elevation tertiles of the grid cells. In Birere, this resulted in strata (1) below 1429 m (2) 1429–1491 m and (3) above 1491 m. In Rugaaga, this resulted in strata (1) below 1442 m (2) 1442–1499 m and (3) above 1499 m. Three grid cells were randomly selected in each elevation stratum. In each of these cells, five random points were sampled, and the nearest homestead was included in the final household selection. Thus, in total, 45 households were selected per sub-county, 15 per elevation stratum.

The household survey covered general household characteristics and detailed soil fertility management practices for each banana field managed by the household, such as input types and costs, quantities and frequency of application. All banana fields were visited and measured using a handheld GPS device.

2.3. Locating the origin of manure and manure sampling

Exploratory field visits and discussions with key informants revealed that banana farmers in the study region imported truckloads of manure to manage soil fertility. To investigate the origin, storage, handling and transport, the manure was traced back to the source. By joining manure transport trucks and with guidance from key informants, 20 kraals in five different sub-counties were visited (Figure 1). Semi-structured interviews on cattle and manure management were conducted when the livestock owner was available. Manure samples were taken from 12 kraals at the end of January 2020, during the short dry season in which manure is collected from the kraals. Five samples were taken at different locations within the kraal to cover the variability. A small hole (22 × 22 cm) was dug to the bottom of the kraal (i.e. the soil layer under the manure at 10–15 cm depth), and all the manure from the hole was collected. The manure from the five holes was thoroughly mixed on a polythene sheet, and four sub-samples per composite sample were taken for analysis. Dry matter content of the manure was determined by oven drying to constant weight at 75 °C. Total N was measured after Kjeldahl digestion in concentrated sulphuric acid at 300 °C (Bremner, 1960). Available P and exchangeable K were extracted using the Bray 1 method (Bray & Kurtz, 1945) and ammonium acetate (Doll & Lucas, 1973), respectively. Total N and available P were then determined using colorimetry, while exchangeable K was quantified using a microwave plasma emission spectrophotometer.

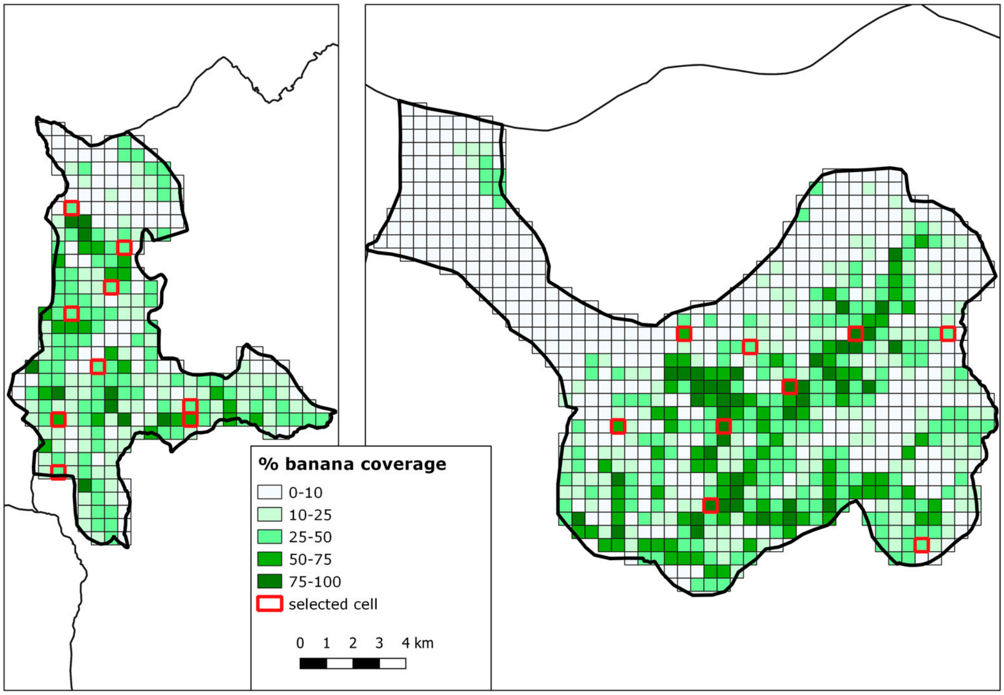

Figure 2. Maps showing the percentage banana coverage in Birere (left panel) and Rugaaga sub-county (right panel).

2.4. Data analysis and secondary data use

2.4.1. Yield range calculation

Banana yields (kg FW/ha/year) were calculated from a 2017 baseline survey in Birere (n = 69) in which bunch weights and mat densities were estimated according to Wairegi et al. (2009). Based on detailed banana field monitoring in Birere (July 2019 to January 2021), we assumed that each mat bears 1.7 bunches per year. Observed median, third quartile, and 90th percentile yields were respectively 37, 45 and 52 t FW/ha/year. The attainable yield was set at 67 t FW/ha/year; the largest observed yield in South-West Uganda (Smithson et al., 2001). Since observed yield data for Rugaaga sub-county were not available, yields were assumed to be the same as for nearby Birere. We used the 90th percentile yields to represent 'intensification'.

2.4.2. Secondary data on livestock

The number of cattle in each sub-county in the manure catchment area was derived from a national livestock census (UBOS, 2009) and translated into Tropical Livestock Units (TLU) (Table 1). Data on manure use by cattle farmers (*n* = 56) were obtained from the TIDE-project (SNV, 2017), which operated in the districts where the catchment area is located.

2.5. Model description and aim

To explore the scope for intensification of banana production in South-West Uganda through crop-livestock integration at a regional scale, a static model, consisting of three sub-models, was developed (Figure 3 and Table 2). The first sub-model calculates N, P and K offtake and N, P and K requirements of banana, and the second sub-model calculates the amount of collectable manure per TLU. Manure and fertilizer requirements for a given banana target yield are calculated in the third sub-model. The objective was to satisfy potassium requirements, through manure application only, or a combination of manure and MOP (Muriate of Potash). The banana fruit has a high K content (Nyombi et al., 2010), resulting in continuous and substantial removal of K. In addition, results from nutrient omission trials conducted in South-West Uganda clearly showed that K is the most limiting nutrient for banana production (Nyombi et al., 2010; Okech et al., 2004). We considered four different input scenarios that refer to the proportion of the K requirement for banana supplied by manure: (1) 100% manure; (2) 75% manure and; (3) 50% manure and (4) 0% manure. The remaining required K is supplied by MOP. The model calculates the number of TLU

Table 1. Characteristics of cattle herds in South-West Uganda.

Category of animals	Mean herd composition (proportion of the herd)[a]	Weight of typical SSA livestock (kg)[b]	Weight of Ankole cattle (kg)[c]	Weight of crossbred cattle (kg)[d]	TLU Ankole cattle	TLU crossbred cattle	Manure excreted by Ankole animal (kg DM/ animal/year)	Manure excreted bycrossbreed (kg DM/animal/year)
Cows	0.495	**250**	**306**	460	1.16	1.58	920	1250
Heifers	0.293	180	220	331	0.91	1.23	719	977
Calves	0.178	75	92	138	0.47	0.64	373	507
Bulls	0.021	320	392	589	1.40	1.90	1108	1504
Steers	0.013	320	392	589	1.40	1.90	1108	1504

[a]Mean herd composition in what is now Isingiro and Kiruhura district (Wurzinger et al., 2008).
[b]Njuki et al. (2011).
[c]Byenkya (2004).
[d]Mulindwa et al. (2008) for crossbreed (Ankole*Friesian) cow. Sources 3 and 4 only report the weight of adult cows (in bold). The weight for other sex and age classes are calculated relative to weights of typical SSA cattle by Njuki et al. (2011), presented in column 3.

required, partial N and P balances and the annual input costs.

2.5.1. First sub-model: nutrient offtake and potassium requirements

Nutrient offtake for N, P and K was calculated by multiplying banana yield by the nutrient percentage in a banana bunch (1.09, 0.11 and 3.55, for respectively N, P and K (IITA, unpublished field experiment data)). Nutrient requirements (kg/ha/year) were calculated based on offtake, nutrient recovery fractions and indigenous soil nutrient supply:

$$\text{Nutrient requirement} = \frac{(BY \times (NP_i/100)) - INS_i}{NR_i} \quad (1)$$

where BY is the banana yield (kg DM/ha/year); NP_i is the percentage of nutrient i in a bunch (kg K/kg DM); INS_i is the indigenous nutrient supply i (kg/ha/year) and NR_i is the nutrient i recovery fraction (–).

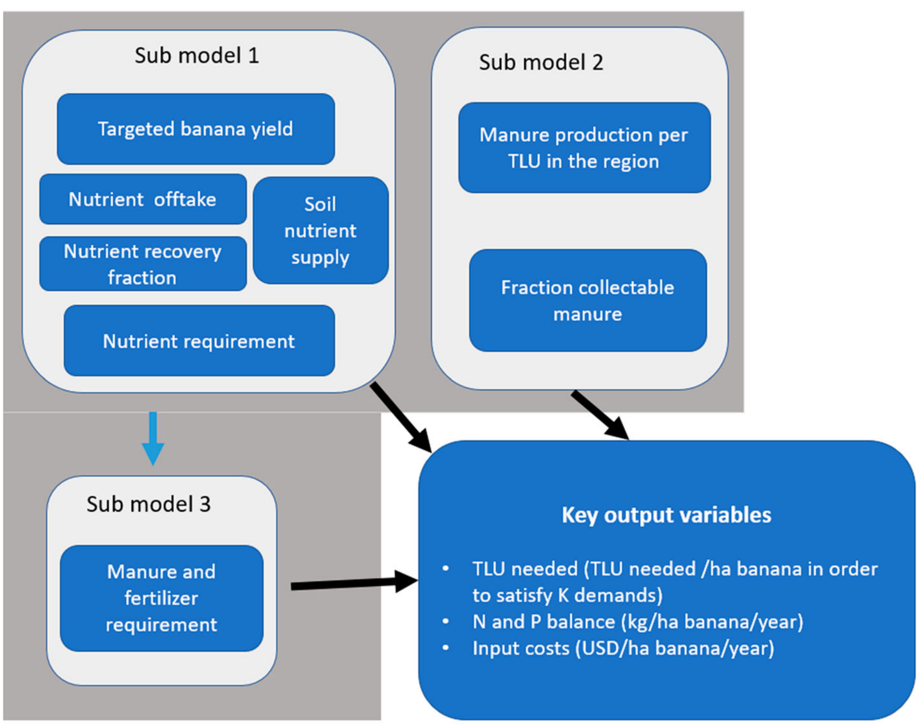

Figure 3. Graphical representation of the model. TLU stands for Tropical Livestock Unit.

Table 2. Baseline values of parameters used to model banana manure and fertilizer requirement, number of TLU required, partial nutrient balances and input costs.

Parameter	Sub-model	Baseline value	Unit	Range	Range description	Source
Yield	1	30.8	t FW/ha/year	30.8–67	median observed – attainable	IITA, unpublished field monitoring data; Smithson et al., (2001)
N recovery	1	0.5	fraction			Nyombi et al., (2010)
P recovery	1	0.3	fraction			Nyombi et al., (2010)
K recovery	1	0.75	fraction			Nyombi et al., (2010)
N soil supply	1	102	kg N/ha/year			Adjusted from Nyombi et al., (2010)
P soil supply	1	10.7	kg P/ha/year			Adjusted from Nyombi et al., (2010)
K soil supply	1	112	kg K/ha/year			Adjusted from Nyombi et al. (2010)
Bodyweight standard cow	2	270	kg bodyweight			See Table 1
Manure production factor	2	12.58	kg DM manure/kg metabolic body weight	Up to 14	full range	Herrero et al. (2013)
Kraal hours	2	13	hours/day	4.5–14	full range	Own data collection
Manure mass loss	2	0.47	fraction			Tittonell et al. (2010)
Stocking density	2	1.74	TLU/ha pasture	1.74–2.34	median – third quartile	Byenkya (2004)
N content manure	3	0.82	% in DM manure	0.55–0.82–1.17	quartiles	Own data collection
P content manure	3	0.08	% in DM manure	0.06–0.08–0.1	quartiles	Own data collection
K content manure	3	1.11	% in DM manure	0.75–1.11–2.6	quartiles	Own data collection
Manure fresh to dry weight	3	0.54	conversion factor (–)	0.48–0.71	full range	Own data collection
Manure price FW	3	19.80	US$/t FW	17.40–21.13	full range	Own data collection
MOP price	Key output	0.79	US$/kg			Own data collection

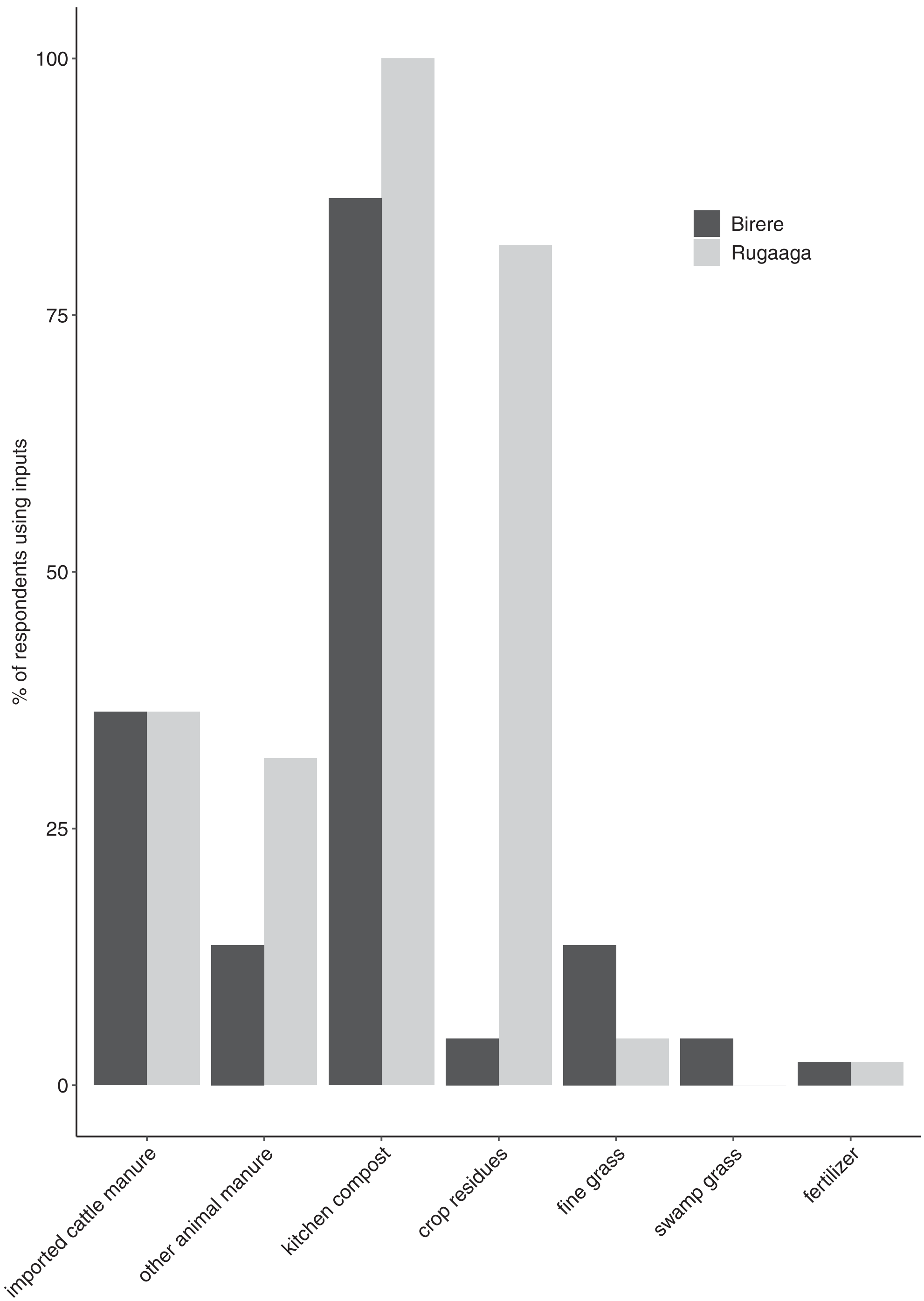

Figure 4. Percentage of respondents using inputs in at least one of their banana fields in Birere (n = 45) and Rugaaga (n = 45) sub-counties.

Median banana yields in the region are estimated at 37 t FW/ha/year (Section 2.5; Table 2) or 5661 kg DM/ha/year (15.3% DM) (Taulya, 2015). Recovery fractions for N, P and K were set at respectively 0.50, 0.30 and 0.75 (Nyombi et al., 2010). Indigenous soil nutrient supply in banana plantations in South-West Uganda was estimated at 60, 6.3 and 66 kg N, P and K/ha per cycle (Nyombi et al., 2010) and the median number of cycles per year in Birere was 1.7. Hence we set the indigenous soil supply of N, P and K at respectively 102, 10.7 and 112 kg/ha/year. If the indigenous soil supply was equal or higher than the crop nutrient offtake at a given target yield, we assumed that no nutrient addition was needed.

2.5.2. Second sub-model: manure production per TLU

Manure production per cow (kg DM/cow/year) is calculated following Herrero et al. (2013):

$$\text{Manure production} = BW^{0.75} \times MP \quad (2)$$

where BW is the body weight of a cow (kg); MP is the manure production factor (kg DM manure/kg metabolic body weight), which is 12.58 for grazing dairy cattle in tropical highlands (Herrero et al., 2013). The body weight of a 'standard cow' was calculated from the average age composition of the herd (Wurzinger et al., 2008), and the fraction of local Ankole (0.805) and crossbred livestock (0.195) in an average herd in the study region (UBOS, 2009). This 'standard' cow was translated into TLU, following Njuki et al. (2011).

Only the manure excreted in the kraal overnight is available for collection, and during storage in the kraal, mass loss of manure occurs (Rufino et al., 2007).

The fraction collectable manure is calculated as:

$$\text{Fraction of collectable manure} = (T_{kraal}/24) \times (1 - \text{mass loss}) \quad (3)$$

where T_{kraal} is the number of hours per day that livestock spent in the kraal and mass loss is the fraction of DM manure mass lost during storage.

The median number of hours livestock spent in the kraal was 13 (own data collection). We used a mass loss fraction of 0.47 based on manure storage experiments in Kenya that found 47% of the initial DM mass of an uncovered manure heap was lost after half a year of storage, and virtually all losses occurred during the first three months (Tittonell et al., 2010).

2.5.3. Third sub-model: manure and fertilizer requirement

The amount of manure required per ha of banana (kg DM/ha/year) is calculated in the third sub-model, based on the calculated K requirement, the K concentration of manure, and the fraction of K supplied by MOP:

$$\text{Manure needed} = (K_{req} - (K_{MOP} \times K_{req}))/(K_{man}/100) \quad (4)$$

where K_{req} is the K requirement (kg/ha/year); K_{man} is the K concentration in DM manure (%); K_{MOP} is the Fraction of K_{req} supplied by MOP.

The amount of MOP required is calculated in a similar way as described for manure, at a K concentration in MOP of 50.22%.

2.5.4. Key outputs

The number of TLU required to supply sufficient manure for 1 ha of banana is based on the manure production per TLU and calculated as:

$$TLU_{\text{required}} = \frac{Man_{req}/Man_{TLU}}{FCM} \quad (5)$$

where $TLU_{required}$ is the number of TLU required to fertilize 1 ha of banana; Man_{req} is the manure required (kg DM manure/ha/year); Man_{tlu} is the manure production per TLU (kg); FCM is the fraction of collectable manure.

The area of rangeland needed to produce enough manure to fertilize 1 ha of banana (the rangeland: cropland ratio) is based on the TLU required and stocking densities as presented by Byenkya (2004) and calculated as

$$\text{Rangeland cropland ratio} = \frac{TLU_{required}}{SD} \quad (6)$$

where SD is the stocking density in rangeland area (TLU/ha rangeland)

Partial N and P balances (kg/ha/year) for banana are calculated as

$$\text{Partial nutrient balance } i = Nut_{in}\, i - Nut_{req}\, i \quad (7)$$

where $Nut_{in}\, i$ is the nutrient input of nutrient i (kg/ha/year) and $Nut_{req} i$ i s the nutrient requirement for nutrient i.

Given the K requirement, the model calculates the fertilizer costs (USD/ha/year) for a given combination of manure and MOP:

$$\text{Input costs} = (Man_{req} \times P_{man}) + (MOP_{req} \times P_{MOP}) \quad (8)$$

where P_{man} is the manure price (USD/kg DM); MOP_{req} is the MOP required (kg/ha/year); P_{MOP} is the MOP price (USD/kg).

2.5.5. Regional supply and demand for manure

The potential supply of manure from the catchment was estimated from the catchment area size (Figure 2), stocking densities in the catchment areas (2.4.2), manure production per TLU (Equation (2), and the prevailing manure storage practices (Equation (3). The regional demand for manure was estimated from the area under banana cultivation in the two study sub-counties (Figure 1) and the nutrient requirements (Equation (1) at a given target yield.

2.6. Model sensitivity analysis

Many input parameters presented in Table 2 are highly variable (e.g. N and K content in manure) or uncertain (K recovery fraction). A sensitivity analysis was conducted by changing each of the input parameters by −20% and +20%, in steps of 5%, while the other parameters were kept constant. The sensitivity of each of the model outputs to each of the input parameters is expressed as the sensitivity index (SI):

$$SI = \frac{((Out + 20\%) - (Out - 20\%))}{Out\ 0}$$

where Out+20%, Out−20%, and Out0 refer to the respective model output for parameters deviating +20, −20 and 0% from the baseline values.

3. Results

3.1. Soil fertility management practices in banana systems

Banana cultivation in the study region is dominated by smallholder farmers cultivating small areas of banana (on average 0.4 and 1 ha in Birere and Rugaaga, respectively) alongside other crops such as beans, maize and groundnut (Table 3). Banana was the main source of income for 55% and 75% of the respondents in respectively Birere and Rugaaga. Most households owned animals – mostly chickens and goats – but this was of minor importance as 78% of the households owned less than one TLU. Respondents were well-aware of the relatively large nutrient demand of bananas and it was prioritized above other crops in terms of nutrient inputs. Hence, nutrient supply to banana fields relied largely on on-farm recycling of nutrients from kitchen waste and crop residues, and on imported cattle manure. Imported manure was used by 35% of the respondents, whereas mineral fertilizer was hardly used at all. Much of the compost consisted of recycled banana peels. Crop residue application – mainly beans and maize – was more widely practiced in Rugaaga because more farmers planted these crops as compared to Birere. However, absolute quantities of crop residues were limited due to the relatively small sizes of these plots (median reported size is 0.3 ha). Imported manure was used on a substantial share of the banana area (Figure 5A,B) with 26% and 44% of the banana area in respectively Birere and Rugaaga receiving manure applications exceeding 2 t DM/ha/year (Figure 5C). However, over 60% of households in both sub-counties did not use any animal manure. Median applications rates in fields receiving manure were 3.4 and 5.9 t DM/ha/year in respectively Birere and Rugaaga. The manure was usually applied to banana prior to the start of the rainy season.

Local truck transporters were transporting manure from the pastoral rangelands up to 50 km away to the banana production areas. Banana trucks returning empty from urban centres were sometimes used for this purpose, but more often, specialized transporters organized transports on demand by banana growers. Manure management by cattle farmers was minimal: manure is deposited, left in the kraal and collected once or twice a year during the dry season. Manure was not heaped or composted, so banana farmers added a mix of fresh and old manure to their fields. Median nutrient concentration (% in DM) was 0.82, 0.08 and 1.11 for N, P and K, respectively, but there was a huge variation, especially for K (Table 2).

Table 3. Characteristics of banana growing households in Birere and Rugaaga.

	Number of fields	Number of banana fields	Average banana area cultivated (ha/household)	% of households with bananas as the main source of income	% owning less than 1 TLU	TLU owned[a]
Birere	1.7 (1.0)	1.4 (0.8)	0.4 (0.4)	55	78	2.54 (3.44)
Rugaaga	2.6 (0.7)	1.4 (0.6)	1.0 (1.9)	75	78	1.87 (2.44)

Note: Means are presented, standard deviations between brackets.
[a]This refers to the average TLU (Tropical livestock Unit) owned by households that have animals, thus excluding the households not owning any animals.

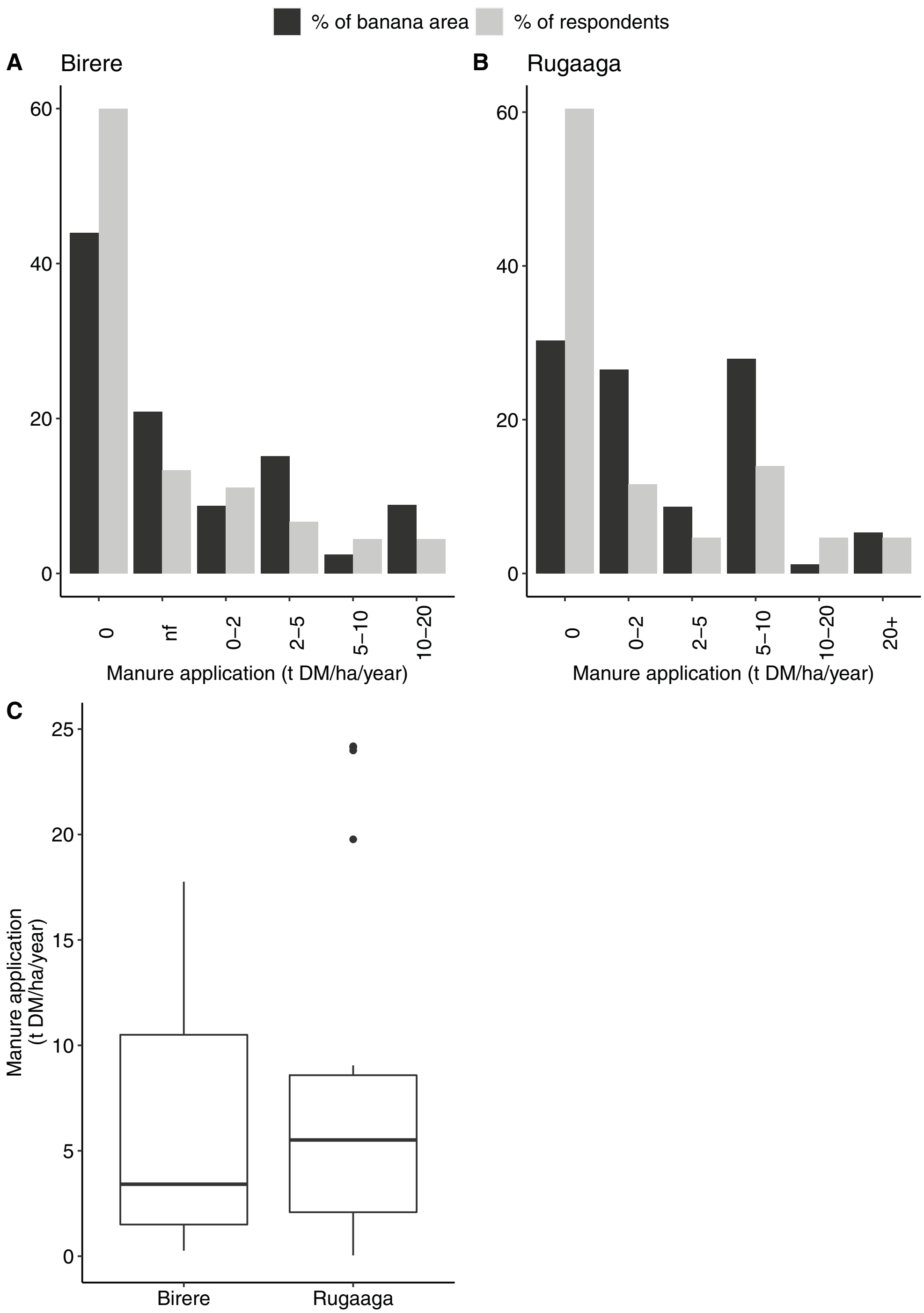

Figure 5. The percentage of the total area with banana to which manure is applied (black bars) and the percentage of households that apply imported manure (grey bars) in Birere (A) and in Rugaaga (B). Figure 5C shows the application rate of imported manure on fields that receive manure. *nf stands for 'no frequent' application. This refers to farmers applying manure infrequently (e.g. once every 5+ years, or only when sufficient money is available).

3.2. Manure requirements and effects on nutrient balances and costs

With median to 90th percentile banana yields (37–52 t/ha/year), and an indigenous soil supply of 112 kg K/ha/year, K requirements ranged from 118 to 228 kg K/ha/year, and to reach attainable yields of 67 t/ha/year, 335 kg K/ha/year was required (Figure 6A). The amount of manure required to satisfy K requirements depended on the input scenario: with a higher percentage of K supplied by mineral fertilizer, the required manure decreased (Figure 6B). If 100% of the required K is supplied with manure, median to 90th percentile yields required 10.5–20.5 t DM manure/ha/year.

Given breed characteristics, herd composition and the type of production system, one Tropical Livestock Unit produced 837 kg DM manure annually, of which 428 kg was excreted in the kraal. After correcting for mass loss during storage, 227 kg DM manure/TLU/year was available for collection. Considering the nutrient concentration of the sampled manure, 1.90, 0.18 and 2.51 kg of respectively N, P and K per TLU/year could be collected. To compensate K requirements at the median to 90th percentile yields, 47–91 TLU were needed per ha of banana (Figure 6B). In the manure catchment area, observed median stocking densities were 1.74 TLU/ha (Byenkya, 2004), resulting in a need for 27–52 ha of rangeland to produce a sufficient amount of manure for one hectare of banana.

By applying large amounts of manure, substantial quantities of nitrogen and phosphorus were also

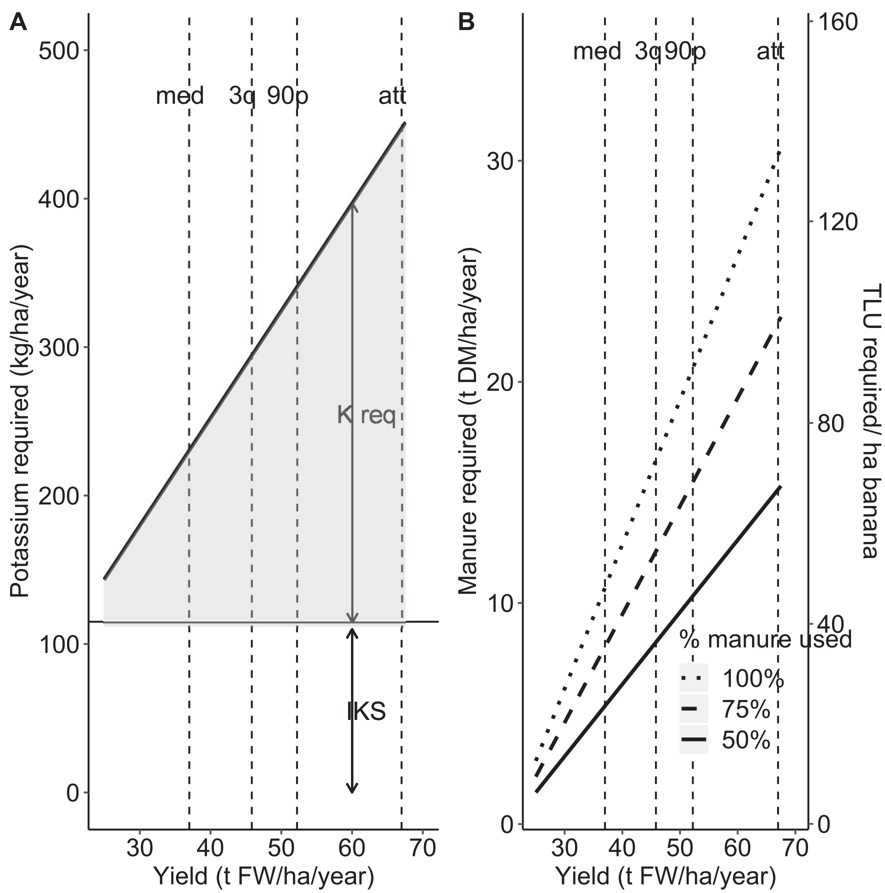

Figure 6. Potassium requirement of banana. IKS is the indigenous soil supply; the shaded area shows the amount of K that has to be added at a given yield level. The solid upper line shows the total potassium requirement of banana (A). The corresponding manure (major *Y*-axis) and TLU required (secondary *Y*-axis on the right) both per ha banana to satisfy K requirements (B). Dashed vertical lines indicate median (med), third quartile (3q), 90th percentile (90p), and attainable (att) yields respectively. In B, the different lines represent the different input scenarios where respectively 100%, 75% or 50% of the total K requirement at a given yield level is supplied by manure, and the remainder is supplied by mineral fertilizer.

applied. When only manure was used to satisfy K requirements at 90th percentile yields (52 t FW/ha/year), the N and P surpluses amounted to 184 and 18 kg/ha/year, respectively. The large N surplus was due to the relatively high soil nitrogen supply compared to N offtake. Furthermore, manure had an unfavourable N:K ratio compared to the offtake of these nutrients in banana: in the harvested bunch, the ratio is roughly 1:3, compared to 1:1.3 in manure. As a result, with increasing manure applications nitrogen surpluses increase considerably. For N and P, indigenous soil supply was sufficient to compensate nutrient requirements at the median to 90th percentile yields, as indicated by the positive nutrient balances in the 0% manure scenario (Figure 7). This means that no additional N and P was needed, except at attainable yields. To achieve a neutral N balance while satisfying K requirements at attainable yields, 1.2 t DM manure was required, combined with 642 kg MOP/ha/year.

Using manure alone was the most expensive option (Table 4). Annual fertilizer costs decreased by 30% when half of the required K was supplied with mineral fertilizer and by 50% in the 0% manure scenario. However, in all scenarios, and regardless of the yield, satisfying K requirements was expensive. Annual input costs at 90th percentile yields (52 t/ha) ranged from roughly 360–740 US$/ha/year, while the value of the produce was 2095 US$/ha.

3.3. Prospects for regional crop-livestock integration

The main determinants of prospects for regional crop-livestock integration were the size of the manure catchment area in relation to the banana area, stocking densities in the rangeland area, and the manure use by cattle farmers (Table 5 and Figure 8). Large amounts of manure were required to provide sufficient K for a hectare of banana. At farm level, manure availability was clearly limited due to strong specialization in crop farming – mainly banana, and hence, small livestock holdings (Table 3). At regional level, the delineation of the size and location of the manure catchment areas (Figure 2) showed that the potential manure availability per hectare of banana strongly differed between sites: 10.5 t DM manure, containing 117 kg K per hectare of banana in Birere and 3.3 t DM manure containing 37 kg K per ha of banana in Rugaaga (Table 5). In Birere, the potential supply of manure was sufficient to satisfy K requirements of the whole area under banana at median yields in the 100% manure scenario (Figure 9A). However, intensification of banana production was not feasible with only manure as a source of K: the manure demand at third quartile and 90th percentile yields were higher than the potential supply. In Rugaaga, the potential manure availability was below the demand in all input scenarios and for all levels of intensification (Figure 9B), implying that maintaining soil fertility – let alone intensification of banana production – solely using manure was not feasible.

In the manure catchment area, cattle farmers allocated manure to a diversity of purposes, with the majority of collectable manure used on-farm for fertilizing arable and fodder crops (Figure 8). This implied that little (an estimated 8%) of the collectable manure was actually available for selling to banana farmers. Therefore, under current circumstances, the actual amount of manure available for application to bananas is much smaller than the potential amount, as shown by the horizontal lines in Figure 9(A,B).

3.4. Model sensitivity analysis

The sensitivity analysis revealed that the soil K supply, the K concentration of manure, and the K recovery fraction had the largest influence on model outputs. The manure and TLU requirements and the input costs were especially sensitive to changes in the soil K supply (Table 6) because this constitutes a large part of the total K requirements, especially when yields are low (Figure 6A). This indicates that the estimates of potassium and manure requirements are conservative: if indigenous soil K supply would decrease due to the continuous removal of K from the soil, much more potassium would be needed to satisfy the crop's K requirement. For instance, with zero soil K supply (as opposed to 122 kg/ha/year), the manure requirement to satisfy 90th percentile yields (52 t/ha/year) increased from 21 to 34 t DM manure/ha/year (Figure 10), thus increasing the discrepancy with the potential regional manure supply. The N and P balances were sensitive to changes in the indigenous soil supply, nutrient recovery fraction and nutrient concentration in manure. Despite this sensitivity, the risk of N losses is considerable, because of the large N surpluses, especially in the 100% manure scenarios (Figure 7A).

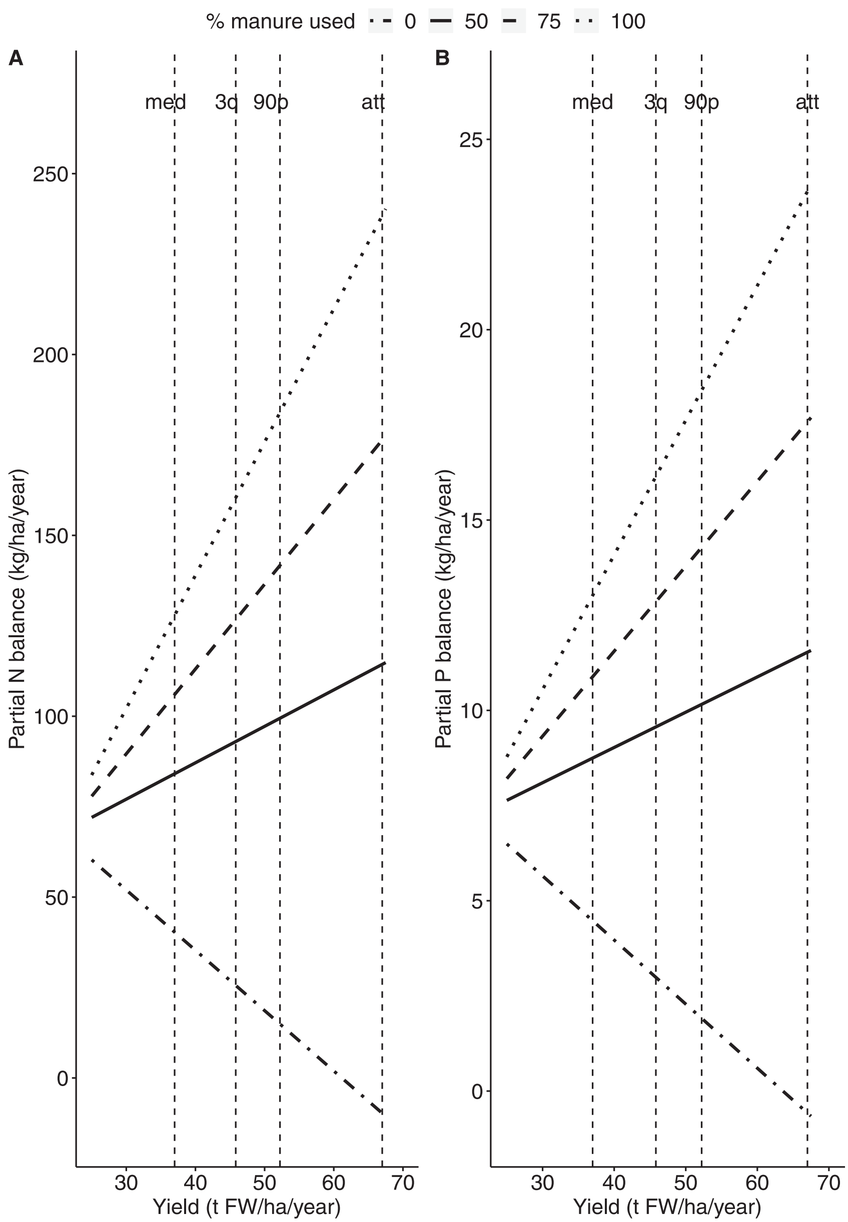

Figure 7. Nitrogen (A) and phosphorus (B) partial balances under different yield targets and input scenarios. Dashed vertical lines indicate median (med), third quartile (3q), 90th percentile (90p) and attainable (att) yields, respectively. The lines represent the different input scenarios where respectively 100%, 75% or 50% or 0% of the total K requirement at a given yield target is supplied by manure, and the remainder is supplied by mineral fertilizer.

4. Discussion

4.1 Potential and limitations of regional crop-livestock integration

Our findings show that while regional crop-livestock integration has considerable potential for alleviating nutrient deficits in banana-based cropping systems, the amounts of manure available were insufficient to intensify banana production. The crop's high potassium requirement resulted in huge manure requirements: 90th percentile yields of 52 t FW/ha/year required 228 kg K/ha/year, for which 20.5 t DM manure were required. Currently, the majority of farmers do not use any manure, while median

Table 4. Fertilizer costs (US$/ha/year) at different yield targets and different input scenarios: respectively 100%, 75% or 50% of the total K requirement for a given yield is supplied by manure, and the remainder is supplied by mineral fertilizer.

			% Manure used to satisfy K requirement			
Yield level	Yield t FW/ha/year	Value of production (US$/ha/year)	0	50	75	100
			Fertilizer costs (US$/ha/year)			
Median	37.0	1563	187	286	385	385
75th percentile	45.8	1826	288	440	591	591
90th percentile	52.2	2095	360	551	742	742
Attainable	67.0	3399	543[1]	810	1090	1090

[a]At attainable yields in the 0% scenario, 1.2 t DM manure is required to achieve a neutral N balance. This is included in the costs.

applications rates in fields receiving manure ranged from 3.4 to 5.9 t DM/ha/year. In terms of resource use efficiency – a key element of sustainable intensification (Struik & Kuyper, 2017) – using only manure is undesirable because of the associated large N surpluses arising from the high indigenous soil N supply and the high N:K ratio in manure. Furthermore, combining manure and K fertilizer is more cost-effective than using manure only. However, intensification of banana production by means of mineral fertilizers alone is not ideal either, because manure fulfills several additional functions to mineral fertilizer. Manure helps maintaining soil organic matter, adds other nutrients to the soil (Zingore et al., 2008; 2011) and improves fertilizer use efficiency (Njoroge et al., 2019). Hence, a more feasible and recommendable way towards intensifying banana production is to combine the available manure with K fertilizer. Mineral fertilizer use in banana production is currently virtually absent due to poor availability, low demand and high perceived costs (van Asten et al., 2010). It is, therefore, urgent to (1) investigate farmers' reservations and (perceived) barriers towards the use of mineral fertilizer on banana; (2) co-evaluate with farmers different combinations of manure and fertilizer through on-farm trials and (3) engage with input suppliers to increase the local availability of mineral fertilizer.

Table 5. Spatial analysis results used to derive potential manure availability.

	Birere	Rugaaga
Total banana area (ha)	1850	4400
% of sub-county covered by banana	24	20
Catchment surface area (km^2)	1133	945
Stocking density in catchment area at district level (TLU/ha)	0.69–0.79	0.69
TLU/ha banana[a]	46	15
Potentially available manure (t DM/ha banana)[b]	10.5	3.3
Potentially available potassium (kg K/ha banana)[b]	117	37

[a]Total TLU present in catchment area divided by total banana area in respective sub-county.
[b]Under the condition that all collectable cow manure in the respective 'manure catchment areas' is applied to banana.

The ratio between crop area and rangeland area was a major factor influencing the prospects for regional crop-livestock integration. Previous research in the Sahel indicated that with crop-livestock integration, a maximum of 10% of the total cropland at village level could be adequately manured each year (Schlecht et al., 2004; Turner, 1995). Findings from Zimbabwe show that 24% of the total village cropland was actively manured (Rufino et al., 2011). In our study region, almost 80% of the banana farmers own less than 1 TLU, and there is little manure available on-farm. Nevertheless, we found that 26 and 44% of the total banana area in respectively Birere and Rugaaga received manure applications of more than 2 t DM manure/ha/year. In Birere, the prospects for regional crop-livestock integration to satisfy banana K requirements were better than in Rugaaga due to an unfavourable rangeland: banana area ratio in the latter sub-county. Despite this, a larger share of the total area in Rugaaga was manured, ad average application rates were also larger. In Rugaaga, a larger share of the households regarded banana as their main source of income than in Birere (Table 3), which may explain the larger manure applications. However, in both sub-counties, substantial amounts of other inputs are needed to deliver sufficient K. Our findings indicate that when manure only is used to satisfy K requirements at 90th percentile yields, approximately 91 TLU per hectare of banana are needed. The total banana area in the four largest banana-producing districts in South-West Uganda (Mbarara, Bushenyi, Ntungamo and Isingiro) was estimated at 0.14 million ha (UBOS, 2010). Consequently, when manure only is used, 12.7 million TLU would be needed to raise banana yields in this area to the 90th percentile yield. This is more than four times the total herd size in the whole of Western Uganda (UBOS, 2009). Although rough and context-

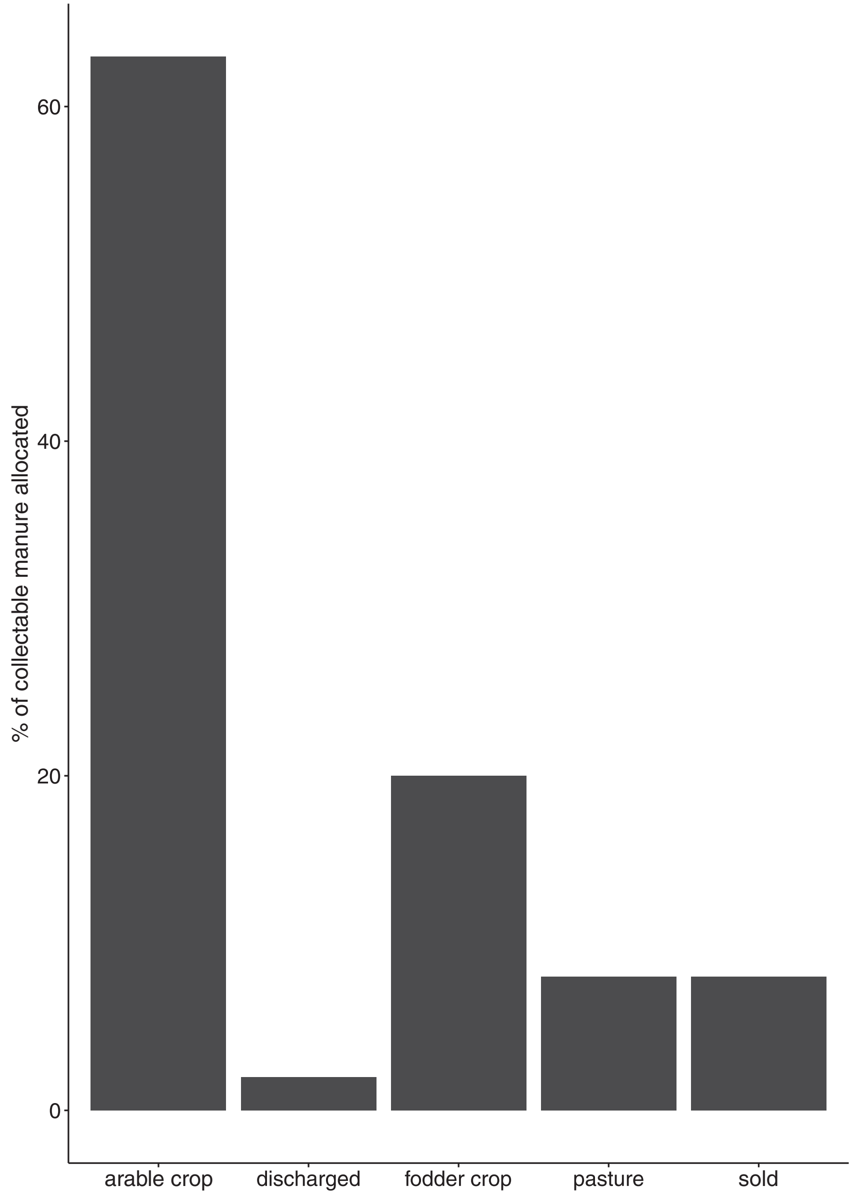

Figure 8. Manure use by cattle farmers taking part in the TIDE-project in the districts where the manure catchment area is located (n = 56). The graph shows the percentage of collectable manure that is allocated for different purposes.

dependent, these estimates confirm that besides manure, substantial amounts of other nutrient inputs are needed for sustainable intensification of banana production in South-West Uganda.

Manure management is another factor determining the prospects for crop-livestock integration. Tittonell et al. (2010) found that only 18% of the total amount of K was retained after manure was stored for six months in an open heap and that most losses occurred in the first few months. Similarly, Rufino et al. (2006) concluded that N cycling through African crop-livestock systems is relatively inefficient and that livestock increases the risk of N loss from the farm system. Hence, the prevailing manure storage method in kraals during the rainy season leads to high nutrient losses and results in poor quality manure. Tittonell et al. (2010) suggest that reducing the storage period in the kraal by more frequent collection and application of manure would be more effective in reducing nutrient losses than improving the conditions under

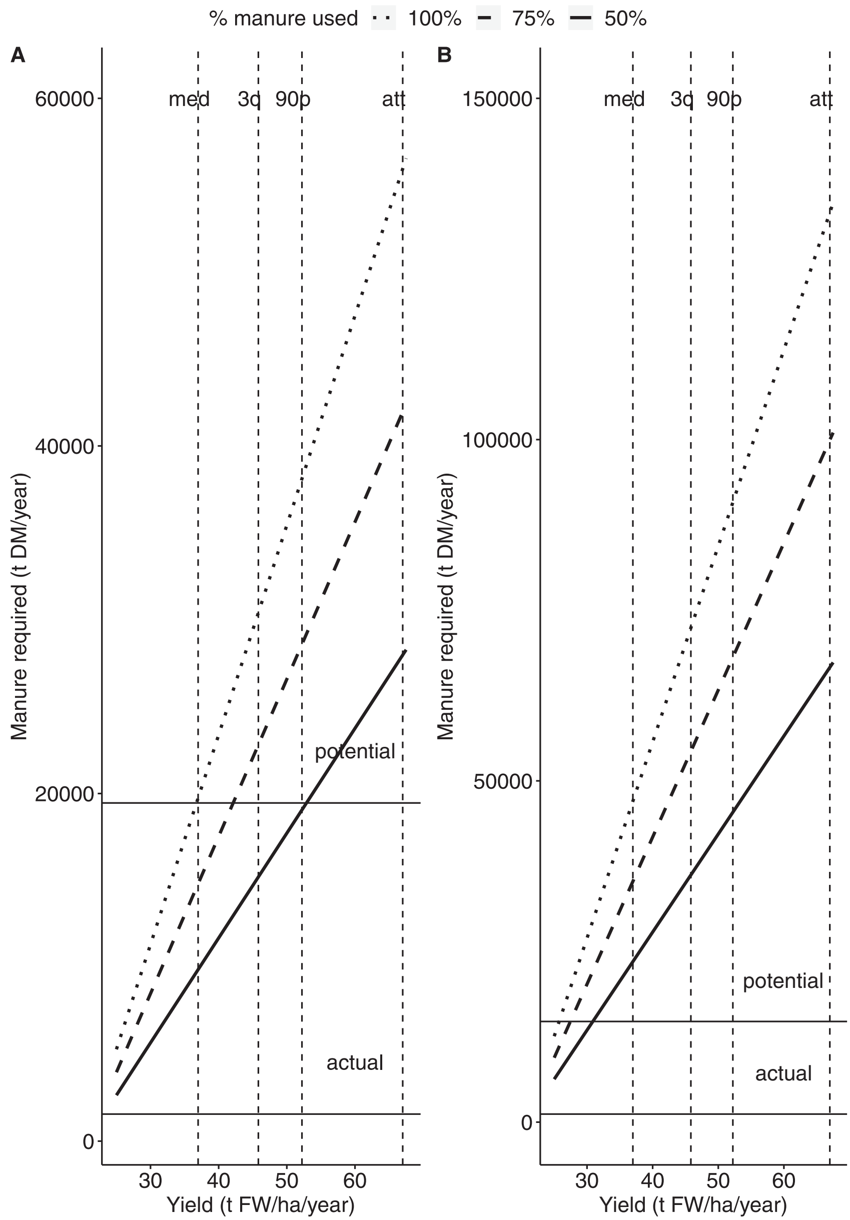

Figure 9. Manure required to satisfy K requirements of the whole area underbanana in Birere (A) and Rugaaga (B). Dashed vertical lines indicate median (med), third quartile (3q), 90^{th} percentile (90p) and attainable (att) yields, respectively. The different lines represent the different input scenarios where respectively 100%, 75% or 50% of the total K requirement at a given yield target is supplied by manure, and the remainder is supplied by mineral fertilizer. In both figures, the upper horizontal line indicates the estimated potential manure availability, and the lower horizontal lines indicate the estimated actual manure availability.

which manure is stored. However, due to the large distance between the manure catchment areas and the banana fields where the manure is applied, increasing the collection and application frequency will come at steep costs and is unlikely to become a feasible option.

The integration of crops and livestock has often been advocated as a promising pathway to improve smallholders' livelihoods (Lenné & Thomas, 2006; Sumberg, 2003). The current banana-livestock integration takes place along the spatial dimension only and follows a source-sink relationship, where the rangelands act as a source of nutrients while the banana areas are 'nutrient-sinks'. In terms of other dimensions – time, ownership and management

Table 6. Sensitivity index of the input parameters influencing model outputs under different scenarios.

Parameter	100% manure	75% manure	50% manure
Model output: TLU required			
Soil K supply	0.81	0.81	0.81
K content manure	0.42	0.42	0.42
K recovery fraction	0.42	0.42	0.42
Kraal hours	0.42	0.42	0.42
Manure_production_factor	0.42	0.42	0.42
Manure mass loss	0.42	0.42	0.42
Model output: Input costs			
Soil K supply	0.81	0.81	0.81
K recovery fraction	0.42	0.42	0.42
Fresh to dry weight	0.42	0.36	0.28
K content manure	0.42	0.36	0.28
Manure price per kg FW	0.40	0.34	0.27
Mop price	0	0.06	0.13
Model output: N balance			
Soil N supply	0.39	0.45	0.52
Soil K supply	0.42	0.36	0.28
K recovery fraction	0.22	0.19	0.15
K content manure	0.22	0.19	0.15
N content manure	0.21	0.18	0.14
Model output: P balance			
Soil P supply	0.4	0.45	0.52
Soil K supply	0.4	0.34	0.26
K content manure	0.2	0.17	0.14
K recovery	0.2	0.17	0.14
P content manure	0.2	0.17	0.13

Notes: Values of 0.4 indicate a proportional change. For each output and scenario, the parameters influencing the output are shown, in descending order of importance. The three input scenarios refer to a situation where respectively 100%, 75% and 50% of the total K requirement is supplied by manure, and the remaining K is supplied by MOP.

(Sumberg, 2003), the systems are completely segregated. Moraine et al. (2017) emphasized that this type of minimalistic regional integration limits the occurrence of synergies and has relatively few ecological benefits as compared to other more intensive types of integration.

4.2. Methodological considerations

The K requirement of banana is central in our approach because it determines the amounts of manure and fertilizer required. We assumed a linear increase in K requirements with increasing target yields, which resulted in K requirements ranging from 118 to 335 kg K/ha/year for median to attainable yields of 37–67 t/ha/year. Nyombi et al. (2010) estimate much larger requirements of 840–1670 kg K/ha/year for the same yield range, using a QUEFTS modelling approach. Experiments in Costa Rica showed that in intensive banana plantations, optimal K supply was in the range of 500–560 kg K/ha/year (López & Espinosa, 1998). Our estimations for K requirements were based on K offtake at harvest, a relatively high K recovery fraction, and a high indigenous soil K supply. As such, our relatively low estimates represent the minimum K requirements in the long term, given a certain target yield. In case actual K requirements would indeed be larger, our finding that sustainable nutrient management cannot be based solely on manure would be reinforced. Nutrient concentrations in manure were in line with findings from Kenya under similar storage conditions (Lekasi et al., 2003). We calculated that approximately 227 kg DM manure could be collected from one TLU per year, which is similar to amounts reported in the literature. For instance, Fernandez-Rivera et al. (1995) estimated that 265–315 kg DM manure per cow could be collected from kraals during a nine-month period.

At present, the majority of banana farmers do not use manure, but the use of mulch from crop residues such as beans and maize and from banana peels and peduncles is widespread. Mulching is beneficial in terms of weed suppression (Wairegi & van Asten, 2010) and water retention (van Asten et al., 2011), but crop residues play only a minor role in terms of nutrient addition. For instance, assuming all peels and peduncles from home-consumed banana can be recycled, we estimated that at median yields, households could recycle a mere 11 kg K/ha, or 10% of the K requirement at median yields. Furthermore, the small size of maize and bean plots hamper the addition of larger quantities of mulch.

Another important consideration follows from the likely over-estimation of manure availability at regional level due to the likely overlap between the manure catchment areas of different banana-producing sub-counties. However, the most stringent limitation to regional crop-livestock integration is that cattle farmers also use manure on their own crops, resulting in a large gap between the actual and potential manure availability. Key informants explained that in the last decade, an increasing number of cattle farmers are venturing into arable farming, with banana being the most important crop. Furthermore, dairy development initiatives in the region promote the cultivation of fodder crops, on which manure is also applied (SNV, 2017; Figure 8). Due to these developments, reaching the full potential of regional banana-livestock integration seems unlikely.

The sensitivity analysis affirmed our main findings on the prospects for crop-livestock integration: varying the parameters to which the model was

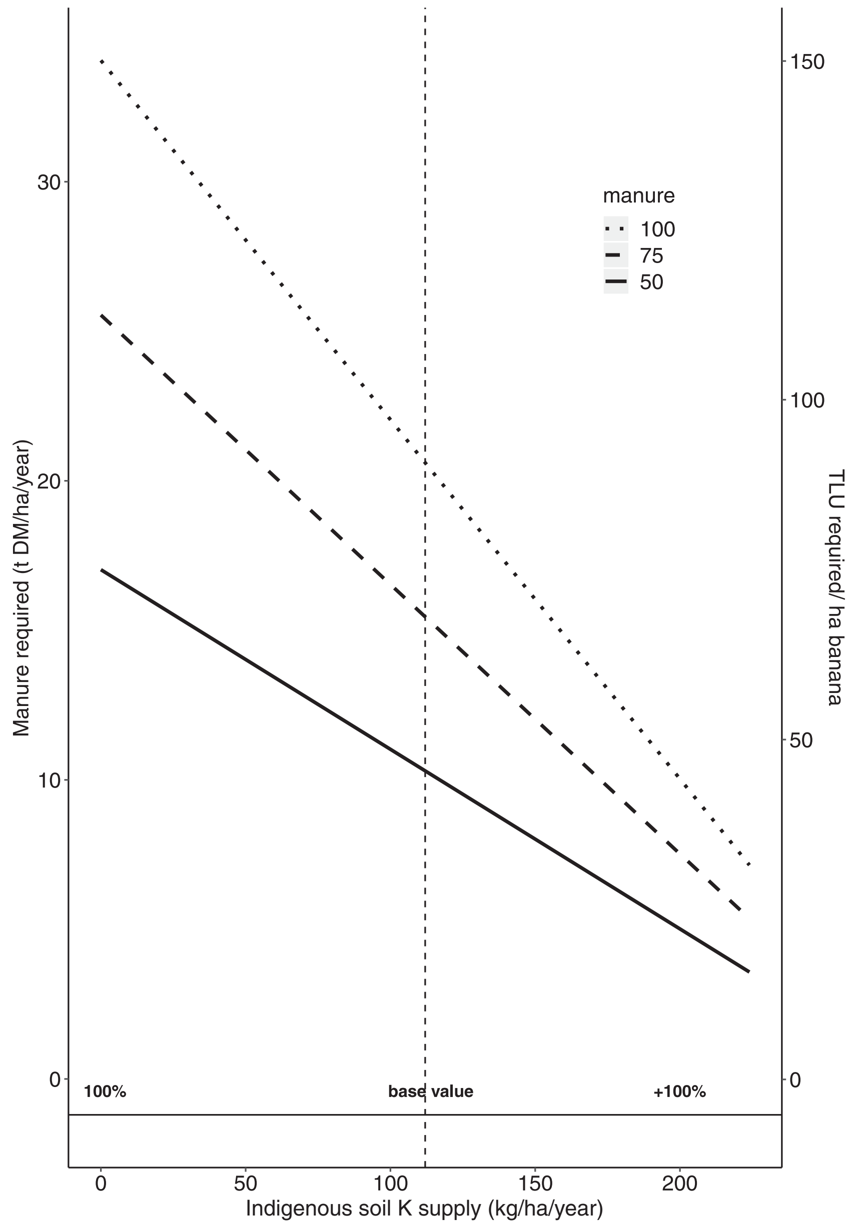

Figure 10. Changes in manure required (major Y-axis) and TLU required (secondary y-axis) when varying the indigenous soil K supply by 100% and +100% from the baseline value of 112 kg/ha/year. The upper, middle and lower lines show the changes in outputs for respectively the 100%, 75% and 50% manure scenario.

most sensitive did not affect the conclusions regarding the manure shortage at regional level, N surpluses or cost-effectiveness in any major way.

5. Conclusion

Banana is a main food and cash crop in South-West Uganda, and farmers consider the application of manure as the single most important determinant of good yields. Consequently, the high demand for manure, in combination with very limited on-farm manure availability, led to a transition to regional banana-livestock integration by means of manure transports over distances of up to 50 km. Our results imply that regional crop-livestock integration has resulted in considerable amounts of manure becoming available, far more than what could be achieved at the farm and village level. The main factors influencing the prospects for regional-level banana-livestock integration are the number of livestock in the vicinity of banana production areas and the manure management and use by cattle farmers. Further integration could increase manure availability, yet we found that even the total potential supply of manure at the regional level is insufficient to meet K requirements for the sustainable intensification of the current banana area in South-West Uganda. If manure would serve as the sole supply of K, far more N would be added than required by banana, resulting in large and undesirable N-losses to the environment. In addition, annual input costs to meet K requirements were lower when manure was combined with mineral fertilizer. Manure has important functions for soil fertility beyond the addition of K, such as maintaining soil organic carbon, adding other nutrients and increasing fertilizer use efficiency. Hence, for sustainably raising banana yields, it would be advisable to combine the available manure with K-based fertilizers, from production, environmental and economic perspectives.

Acknowledgements

We thank all farmers, key informants and field assistants for sharing information and knowledge and for spending their valuable time with us. The authors are thankful to the SNV TIDE project in Mbarara for providing data on manure use by cattle farmers. We thank Irene Parisi for the assistance with the modelling.

Data availability and deposition

Data and R code used for the analyses can be accessed here: https://doi.org/10.4121/16628245.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The authors acknowledge the funding from the International Institute of Tropical Agriculture (IITA) Crops Research Project on Roots, Tubers and Bananas for sharing input data for the modelling activities.

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