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Effect of grass-diet and grass-legume-diet manure applied to planting holes on smallholder maize production in Rwanda

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ABSTRACT

Animal manure provides plant nutrients and also affects soil nutrient availability, pH buffering and soil physical properties through its contribution to soil organic matter pools. However, the quality and quantity of manure are often low on smallholder farms in sub-Saharan Africa and the initial effect of manuring on crop yield may be small or even negative. In a two-factorial experiment over four seasons in southern Rwanda, the fertiliser value to a maize crop of manures produced by cattle fed a basal diet of only *Chloris gayana* grass or a mixed *C. gayana-Acacia angustissima* diet was compared with that of NPK 17−17−17 and no fertiliser. The potential liming effect of the manures was also evaluated through inclusion (or not) of travertine as the second factor. All amendments were applied only to maize planting holes. The crop failed in season 1 due to drought, but manure application (5 t ha^{-1}) approximately doubled maize yield compared with the unfertilised control during seasons 2–4, while NPK (70 kg N ha^{-1}) increased yield by 3- to 4-fold, with corresponding improvements in crop performance indicators. The mixed diet increased manure quality and maize yield compared with the grass diet in season 4. Liming showed a consistent tendency to improve crop performance indicators and yield, but significant differences were only identified in some cases, possibly because the pH increase was small. The results suggest that in regions where manure availability is limiting, application of reduced rates only to planting holes may be an efficient technology. Enhanced animal feed can result in higher quality manure, and ultimately increase crop yield, if nutrient losses during manure handling and storage can be limited.

1. Introduction

In sub-Saharan Africa (SSA), agriculture plays an important function in economic growth and rural livelihoods. However, low soil fertility and ongoing loss of soil nutrients and organic matter negatively affect agricultural productivity on many farms in SSA (Vanlauwe et al., 2010a; Bationo et al., 2012; Tully et al., 2015). With increasing population in the region, dietary changes and a need for production of e.g. fibre and fuel on a finite area of land exploitable for agriculture, the productivity of current agricultural land needs to increase. To this end, the supply of plant nutrients to farmland via inorganic fertilisers and organic sources, if possible in combination, needs to increase. However, the fertiliser rates recommended by agronomists are beyond the reach of many smallholder farmers, which has led to the development of micro-dosing technology (Bationo et al., 2012; Ibrahim et al., 2016; Tovihoudji et al., 2017). In micro-dosing, mineral fertilisers are applied at lower rates and only to crop planting holes where the close proximity between roots and fertiliser enhances nutrient access and use by the crop. The positive effect of micro-dose fertilisation has been well documented for cereal crops and is reported to result in higher fertiliser use efficiency and require a smaller financial investment, making it a suitable technology for resource-poor smallholder farmers (Aune et al., 2007; Hayashi et al., 2008; Bagayoko et al., 2011; Camara et al., 2013).

Animal manure is an important source of plant nutrients, but also influences the availability of other nutrients in soil through its supply of organic matter (Bayu et al., 2004) and increase in pH in acid soils (Mucheru-Muna et al., 2014). However, in SSA the concentrations of nutrients in manure and nutrient release rates are frequently low,

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because of low feed quality and poor manure handling and storage (Naramabuye and Haynes, 2006; Sileshi et al., 2017), and combined application of organic inputs and inorganic fertilisers is recommended as part of integrated soil fertility management (ISFM) (Vanlauwe et al., 2011). Animal productivity in SSA is often constrained by low feed quality. Supplementing low-quality basal feeds with protein-rich concentrates is a challenge for smallholder farmers with low income, but leaves from leguminous trees/shrubs can be valuable sources of proteins and minerals for smallholder ruminant animals (Simbaya, 2002). Enhanced feed protein concentration is known to increase the nitrogen (N) concentration in the manure produced (Lekasi et al., 2002; Muinga et al., 2007). Supplementation of otherwise protein-poor animal diets with protein-rich legume shrub leaves may thus enhance animal productivity and manure quality. In addition to the shortfall in quality, it may be difficult to source the required quantity of manure. Animal manure is in short supply in some SSA countries, such as Rwanda, due to limited livestock numbers. The manure application rates required to achieve a sustainable increase in crop yields are therefore generally not achievable by smallholder farmers in SSA (Mapfumo and Giller, 2001).

Large areas of the Tropics are dominated by strongly weathered acid soils, such as Ferralsols and Acrisols. Strongly acidic soils are unsuitable for many arable crops, as they contain excessive concentrations of exchangeable Al^{3+} and low availability of phosphorus (P) and other plant nutrients such as potassium (K), calcium (Ca) and magnesium (Mg). Increasing soil pH is needed to enhance land productivity and soil suitability for a wider range of crops, but farmers face challenges in accessing and paying for bulky and heavy lime. Young plants have been shown to be more sensitive to aluminium toxicity than older plants (Wheeler, 1994), so concentrating small amounts of lime and/or animal manure to crop planting holes (the soil environment experienced by very young plants) may maximise the benefit of soil amendment at low overall application rates.

The objective of this study was to investigate a) the effect of cattle manure on maize growth and yield compared with NPK fertiliser when applied at reduced rate only to planting holes, b) the effect of supplementing a basal ruminant diet of grass with a forage legume (*Acacia angustissima*) on manure fertiliser quality and maize growth and yield, and c) the potential liming effect of the manures.

2. Materials and methods

2.1. Site characterisation

A field experiment was carried out at Tonga research station (2°35′S; 29°43′E; 1700 m above sea level), University of Rwanda, Huye, Rwanda. Mean annual temperature at the site is 19.1 °C and mean annual rainfall 1150 mm (Climate-Data.org, 2021). Some rain normally falls in all months, but larger amounts fall during two rainy seasons: September to January (season A) and mid-February to mid-June (season B), with precipitation peaks in November and April (Climate-Data.org, 2021). The experiment was run for four growing seasons (seasons 1–4), from season B in 2016 to season A in 2017 (with harvest in early 2018). All seasons (1–4) were characterised by lower total rainfall than the long-term (1981–2018) average for seasons A and B, respectively, and/or had dry spells during the growing season (Fig. 1).

The soil at the site was formerly a Haplic Ferralsol (FAO, 2006), but has changed to an Anthropic Ferralsol due to radical terracing of the hillside. At the start of the experiment, the soil had a sandy loam texture, with 21 % clay, 15 % silt and 64 % sand, bulk density of 1.23 g cm^{-3}, water-holding capacity of 27 g 100 g^{-1} dry weight (DW) of soil and a water infiltration rate of 230 mm h^{-1} (Mukangango et al., 2020). At that time the soil was acid (pH_{H2O} 4.2; exchangeable Al^{3+} 2.8 cmol kg^{-1}) and had low soil organic carbon (C, 0.64 %), cation exchange capacity (CEC, 5.7 cmol kg^{-1}) and nutrient concentrations (4.9 ppm available P, 0.31 cmol kg^{-1} exchangeable K, 0.48 cmol kg^{-1} exchangeable Ca, 0.16 cmol kg^{-1} exchangeable Mg). The soil was under fallow for more than 10 years prior to the start of the experiment, with the vegetation dominated by *Eucalyptus* spp. and *Eragrostis curvula*. The soil was prepared for planting using hand hoes and machetes and the biomass removed from the plots.

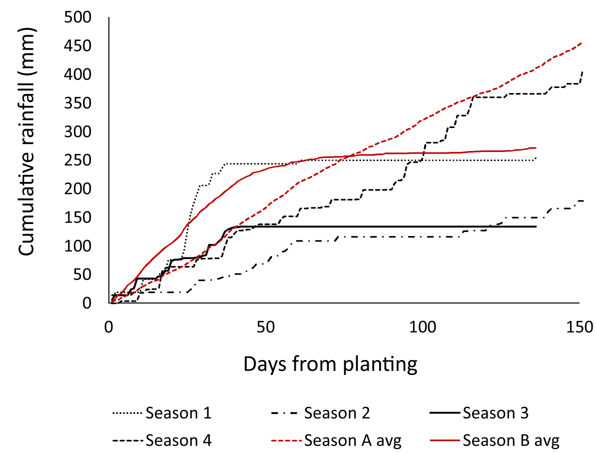

Fig. 1. Rainfall during the experimental period, recorded at the weather station of Butare Airport, Huye, 3 km from the experimental site. Average rainfall for seasons A (Sept-Jan) and B (Feb-June) is calculated from records for the period 1981 to 2018.

2.2. Experimental design

The experiment had a two-factorial, randomised complete block design with four replicates with fixed plots over the four growing seasons (Table 1). Four consecutive bench terraces hosted the blocks, which were each divided into eight 4 m × 3 m plots, with net plots of 2 m × 2 m for observation and sampling. The factors were nutrient input (through manure/inorganic fertiliser application) and liming (travertine). Two types of manures were used, derived from cattle fed different diets. The inorganic fertiliser (NPK17−17−17) served as a positive control (indicating the production potential of the site and growing season) where the N was in the form of ammonium (NH_4^+). The liming material used was travertine (33.3 % Ca and 1.16 % Mg) mined at Mashyuza, western Rwanda. An untreated negative control was included for both factors. The manures were collected from cattle fed either the basal diet of only the commonly used grass *Chloris gayana* or a mixed diet of *C. gayana* supplemented with *Acacia angustissima* at a rate of 30 % DW of the daily ration. The manure storage consisted of composting in pits lined and covered with plastic sheets, which was considered affordable for farmers in the area. The manure was turned frequently during the composting time, which varied between 10 and 12 weeks during seasons 1−4. Before applying the manure in the field experiment, eight subsamples were taken across the bulk of each manure, pooled and analysed for nutrient concentrations and dry matter content, in order to calculate the nutrient application rates.

Given that the availability of animal manure is limited on many

Table 1
Summary of treatments in the trial.

	Factor 2 →:	
Factor 1 ↓:	Travertine	No travertine
Grass- diet manure	5 t ha^{-1} $season^{-1}$ manure 2.0 t ha^{-1} yr^{-1} travertine	5 t ha^{-1} $season^{-1}$ manure –
Grass-legume- diet manure	5 t ha^{-1} $season^{-1}$ manure 2.0 t ha^{-1} yr^{-1} travertine	5 t ha^{-1} $season^{-1}$ manure –
NPK	70 kg N/P/K ha^{-1} 2.0 t ha^{-1} yr^{-1} travertine	70 kg N/P/K ha^{-1} –
No nutrient input	– 2.0 t ha^{-1} yr^{-1} travertine	– –

smallholder farms in Rwanda and that purchasing travertine is associated with high costs, the manures and lime were used at 25 % of the rate recommended by the University of Rwanda. The fertiliser rate was, however, set to reach a recommended total mineral N of 80 kg ha^{-1} (Sallah et al., 2009), based on soil analysis before the experiment. The manure was thus applied prior to maize sowing in each planting season at 5 t DM ha^{-1}, corresponding to 125 g per planting hole. The NPK fertiliser was applied in each planting season at a rate of 70 kg N ha^{-1}, corresponding to 10 g per planting hole in a split dose with 20 % at planting, 40 % at 6 weeks after planting and 40 % at 8 weeks after planting. The lime rate was 25 % of the rate required to neutralise the exchangeable aluminium at the site, equalling a rate of 2.0 t ha^{-1} of CaO or 50 g per planting point. It was applied once a year, before planting the maize.

2.3. Maize management and data collection

Maize (*Zea mays* L., early maturing variety PAN 4M-21) was planted (3 seeds per planting hole) at a spacing of 0.5 m both within and between rows. After germination, the seedlings were thinned to one seedling per planting hole. Weeding was performed manually as necessary. The crop failed in season 1 due to drought. In seasons 2–4, complementary water corresponding to 100 l per plot (8.3 mm) per occasion was applied whenever the rain stopped for more than five days and then on every second day until the rain resumed. Cumulative irrigation amount was approximately 275, 310 and 150 mm in season 2, 3 and 4, respectively. Cypermithrin (5%) was used to control maize stem borer (*Chilo partellus* S.), which was prevalent in the region during the study period. The maize stover was left on plots after harvest and planting holes were retained over all four growing seasons.

Maize data collection started in season 2. Growth data were collected by determining the number of developed leaves, plant height and leaf chlorophyll content on 16 plants in the net plots at 4, 8 and 12 weeks after planting (WAP). Plant height was measured from the ground to the tip of the uppermost leaf. Leaf chlorophyll was measured by taking three readings per leaf, midway from base to tip on the uppermost fully developed leaf, using a Soil-Plant Analyser Development (SPAD-502) meter (Minolta, Japan) (in total 48 readings $plot^{-1}$). At maturity, all plants in the net plots were harvested and the aboveground biomass was weighed. The ears (cob + grains) and stover (stem, leaves and husks) were then separated by hand and weighed separately. The ears were dried at 60 °C to constant weight at 12 % moisture content and shelled to obtain grain weight (kg) for each plot. A subsample of stover was dried for 48 h at 60 °C. Subsamples of the dried grain and stover were further dried at 105 °C and the weight loss during drying was used to calculate total dry weight of the maize yield (tons per ha). Harvest index was calculated as the ratio of grain yield to total aboveground biomass. The amount of N/P/K (kg per ha) in aboveground crop biomass was approximated as:

(Grain yield (kg ha^{-1}) × Grain N/P/K concentration (%) + Stover yield (kg ha^{-1}) × Stover N/P/K concentration (%)) / 100

2.4. Manure and plant analysis

Samples of manure dried at 70 °C and samples of maize grain and stover dried at 60 °C were milled to pass a 2-mm sieve. Total N was determined using the micro-Kjeldahl method (Anderson and Ingram, 1993) and measured colorimetrically. Phosphorus content was determined in the same digest, measured colorimetrically without pH adjustment (Okalebo et al., 2002). Concentrations of Ca, Mg, K and sodium (Na) were determined in the same digest, using an atomic absorption spectrophotometer (VARIAN) (Okalebo et al., 2002). Total C in the manure samples was determined by the Walkley-Black method (Anderson and Ingram, 1993).

2.5. Statistical analysis

Data on manure characteristics were subjected to one-way analysis of variance (ANOVA) to evaluate the effect of the animal's diet, using the four seasons as replicates (JMP® 14.0.0, SAS Institute Inc., Cary, NC, USA). Data on maize yield and on crop N, P and K concentrations were subjected to three-way analysis of variance to evaluate the effect of a) manure/fertiliser application, liming and season, and their interactions and b) manure type (derived from grass diet or mixed diet), liming and season, and their interactions. The data were subjected to two-way analysis of the same treatment effects across all seasons. Crop performance indicators were analysed by season, to evaluate the effect of a) manure/fertiliser application, liming and time since planting (WAP), and their interactions and b) manure type, liming and WAP, and their interactions. In the evaluation of effects of manure/fertiliser application, the two manure types were aggregated. Block and plot were used as random variables, to take account of repeated measurements over seasons or within seasons. Data were log- or square root-transformed when necessary to achieve a normal distribution. When significant effects were found at the 5% significance level, Tukey's multiple comparison test was used to test differences between treatment LSMeans. Data reported are the main effects of the treatments unless otherwise specified and differences described in the text are significant at $p < 0.05$.

Stepwise regression analysis was performed (JMP® 14.0.0) to test correlations between maize grain yield vs stover yield and N, P and K concentrations in the grain and stover. Stover yield was included in the model for grain yield on the assumption that vegetative plant parts form the basis for grain production. Stepwise regression analysis was also performed to test correlations between maize stover yield vs N, P and K concentrations in the stover. Data were normalised prior to analysis and minimum Bayesian information criterion (BIC) was used as the stopping rule.

3. Results

3.1. Concentrations of nutrients in the two manures

Supplementing *C. gayana* grass with *A. angustissima* led to increased concentrations of total N, total C and base cations in the manure (Table 2). The P concentration was unaffected, however, and the C:N ratio and pH of the manures were not significantly different. The composition of the two manure types was similar across all seasons.

Table 2
Chemical composition of the two manure types and application rates of nutrients via the manures (rate 5 t ha^{-1}), given as LSMeans of the four seasons*.

		Manure properties			Application rate via manure	
	Units	Grass diet	Mixed diet	Units	Grass diet	Mixed diet
pH_{H2O}		6.9	7.0			
C	%	17 [b]	20 [a]	t ha^{-1}	0.85	1.0
N	%	1.2 [b]	1.5 [a]	kg ha^{-1}	60	75
C/N		14.1	13.2			
P	g kg^{-1}	6.2	6.2	kg ha^{-1}	31	31
Ca	g kg^{-1}	6.4 [b]	9.3 [a]	kg ha^{-1}	32	46
Mg	g kg^{-1}	2.9 [b]	3.7 [a]	kg ha^{-1}	14.5	18
K	g kg^{-1}	3.1 [b]	6.5 [a]	kg ha^{-1}	15.5	32
Na	g kg^{-1}	0.9[b]	1.4[a]	kg ha^{-1}	4.5	7.0

* The manures were produced by cattle fed 100 % *Chloris gayana* (Grass diet) and cattle fed the grass diet supplemented with *Acacia angustissima* at 30 % of the feed ration (Mixed diet). Data determined after drying material at 70 °C. LSMean values of composition data followed by different letters are significantly different ($p < 0.05$).

3.2. Crop performance indicators

The two experimental years were the third driest (568 mm) and driest (506 mm) in 38 years of recorded rainfall, and the crop failed entirely during season 1, before supplementary watering could be carried out. During seasons 2–4, manure application overall increased the number of maize leaves per plant, maize plant height and SPAD values at the three observation times (4, 8, 12 WAP) compared with the unfertilised control, and the increases were even larger in the NPK treatment (Figs. 2–4A; 12 WAP shown). There was generally no significant difference in the effect of manures derived from cattle fed only grass or the mixed grass-legume diet (Figs. 2–4B). However, maize plant height during season 4 was 10 % higher after application of mixed-diet manure when tested across the three observation times ($p = 0.019$). Liming did not significantly affect crop performance indicators at individual observation times (Figs. 2–4C). When testing across the three observation times, liming slightly increased maize plant height in seasons 2 ($p = 0.006$) and 4 ($p = 0.001$), and increased the number of leaves per plant ($p = 0.021$) and SPAD values ($p = 0.032$) in season 4.

3.3. Maize yields

Yield ranged from 0.5 to 3 t ha^{-1} in seasons 2 and 3, but was approximately triple that level in season 4, when rainfall was more abundant and evenly distributed (see Fig. 1). Applying 25 % of the recommended dose of manure doubled the maize grain yield in all seasons and increased that of maize stover by approximately 50 % (Fig. 5A). The full recommended dose of NPK fertiliser increased yield further, e.g. it increased grain yield by 3- to 4-fold compared with the unfertilised control, reaching a yield of 7 t ha^{-1} in season 4, and almost tripled stover yield. The effect of the two manure types did not differ in seasons 2 and 3, but the mixed-diet manure significantly increased grain yield (by on average 50 %) compared with the grass-diet manure in season 4 (Fig. 5B). Liming generally did not affect yield significantly, but increased stover yield in season 4 (Fig. 5C).

Harvest index was around 0.36 in all treatments in season 2, but increased to around 0.40 in the unfertilised treatments in seasons 3 and 4, when it was also significantly higher in the manured and fertilised treatments (average 0.46; $p = 0.037$ and 0.039 for seasons 3 and 4, respectively). In season 4, the mixed-diet manure significantly ($p = 0.049$) increased harvest index (0.51) compared with the grass-diet

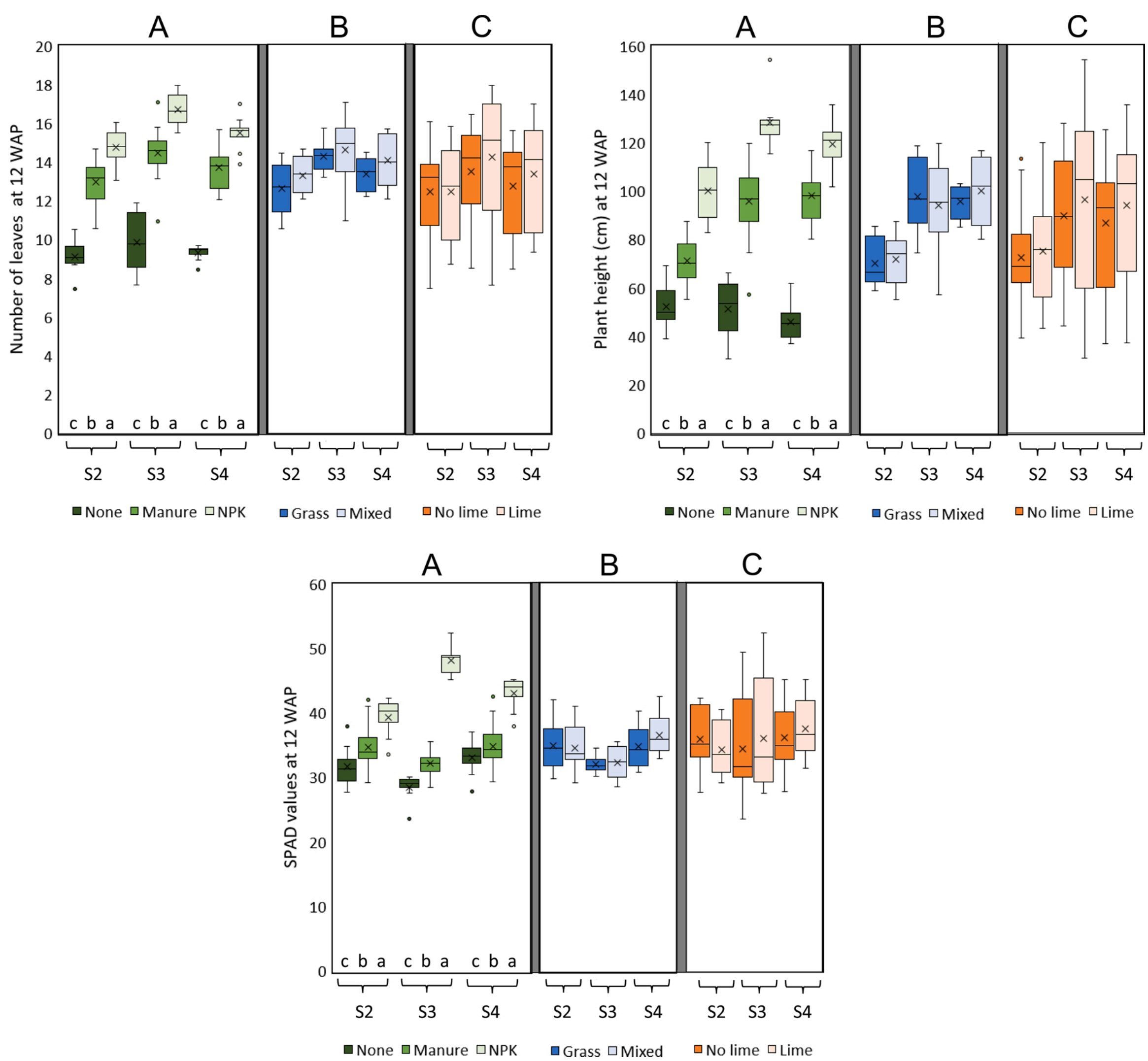

Fig. 2–4. Main effects of (A) fertiliser and cattle manure, (B) manure type and (C) liming with travertine on number of leaves per maize plant (Fig. 2), maize height (Fig. 3) and leaf chlorophyll content (SPAD readings; Fig. 4) at 12 weeks after planting (WAP). Effects of nutrient input (NPK vs manure vs none; mixed-diet manure vs grass-diet manure) and liming (limed vs non-limed) were tested in a two-factorial approach and means are indicated by '×' inside the boxes. 'Manure' in (A) is the average of both types of manure. Parameters are clustered with brackets according to growing seasons 2 to 4 (S2-S4). LSMeans within each cluster marked with different letters are significantly different ($p < 0.05$).

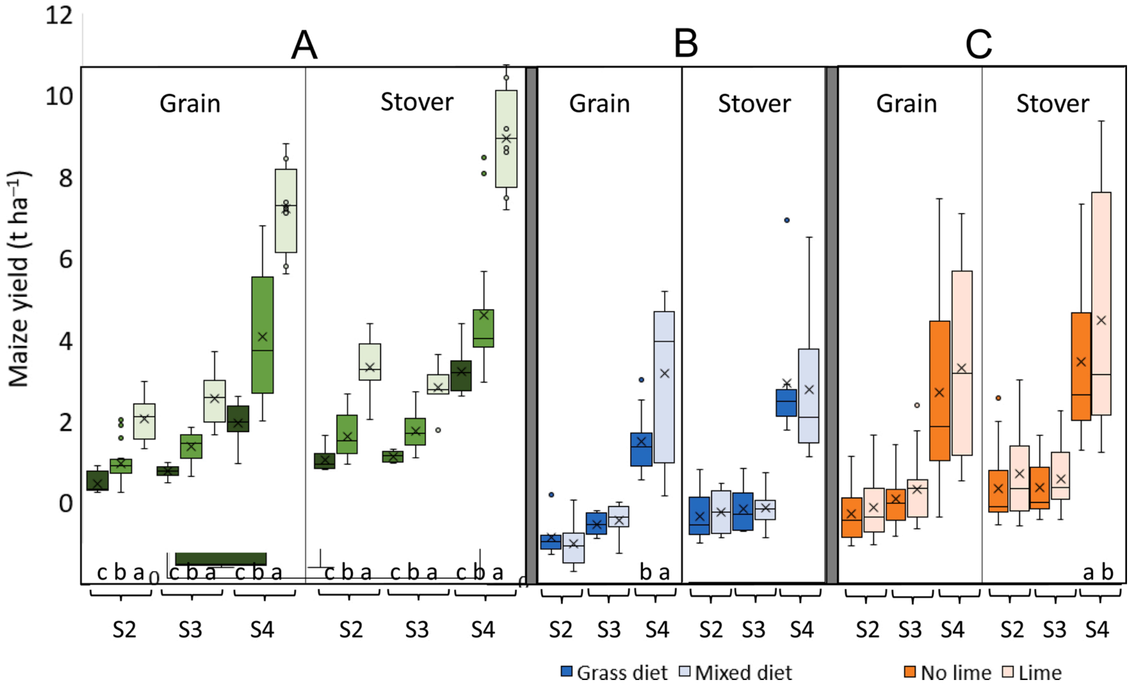

Fig. 5. Main effects of (A) inorganic NPK fertiliser and cattle manure, (B) manure type and (C) liming with travertine on yield of maize grain and stover. Effects of nutrient input (NPK vs manure vs none; mixed-diet manure vs grass-diet manure) and liming (limed vs non-limed) were tested in a two-factorial approach and means are indicated by '×' inside the boxes. 'Manure' in (A) is the average of both types of manure. Parameters are clustered with brackets according to growing seasons 2 to 4 (S2-S4). LSMeans within each cluster marked with different letters are significantly different ($p < 0.05$).

manure (0.42).

3.4. Maize N, P and K concentrations

Grain and stover N, P and K concentrations were generally similar in all treatments in season 2, but the N concentrations were lower in the unfertilised and manure treatments than in the NPK treatment in season 4, and in that season decreased in the unfertilised treatment compared with seasons 2 and 3 (Figs. 6–8A). Further, stover P concentration was higher in both the NPK and manure treatments than in the unfertilised control in all seasons. There were few differences in nutrient concentrations between the maize fertilised with grass-diet manure and mixed-

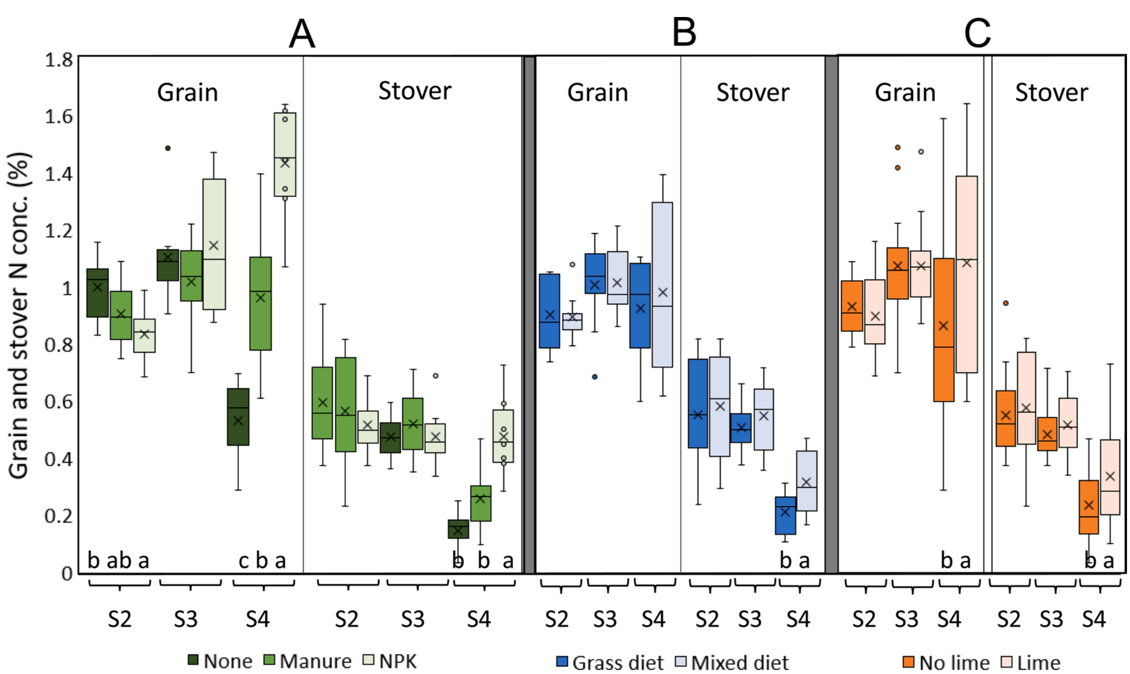

Fig. 6. Main effects of (A) fertiliser and cattle manure, (B) manure type and (C) liming with travertine on nitrogen (N) concentration in maize grain and stover. Effects of nutrient input (NPK vs manure vs none; mixed-diet manure vs grass-diet manure) and liming (limed vs non-limed) were tested in a two-factorial approach and means are indicated by '×' inside the boxes. 'Manure' in (A) is the average of both types of manure. Parameters are clustered with brackets according to growing seasons 2 to 4 (S2-S4). LSMeans within each cluster marked with different letters are significantly different ($p < 0.05$).

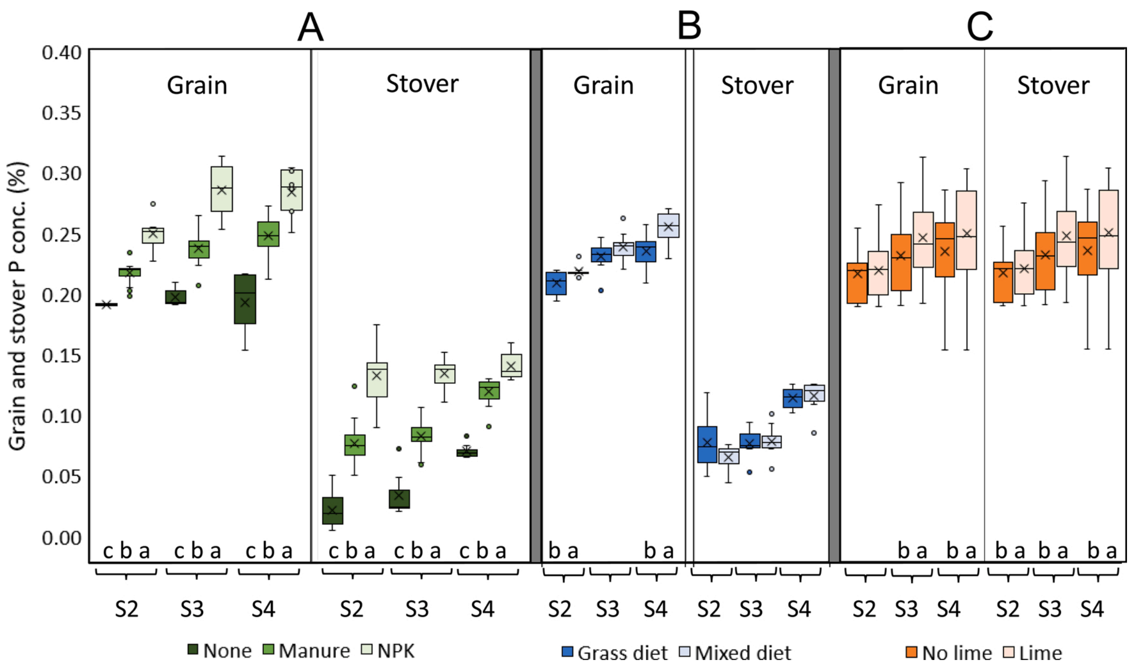

Fig. 7. Main effects of (A) fertiliser and cattle manure, (B) manure type and (C) liming with travertine on phosphorus (P) concentration in maize grain and stover. Effects of nutrient input (NPK vs manure vs none; mixed-diet manure vs grass-diet manure) and liming (limed vs non-limed) were tested in a two-factorial approach and means are indicated by '×' inside the boxes. 'Manure' in (A) is the average of both types of manure. Parameters are clustered with brackets according to growing seasons 2 to 4 (S2-S4). LSMeans within each cluster marked with different letters are significantly different ($p < 0.05$).

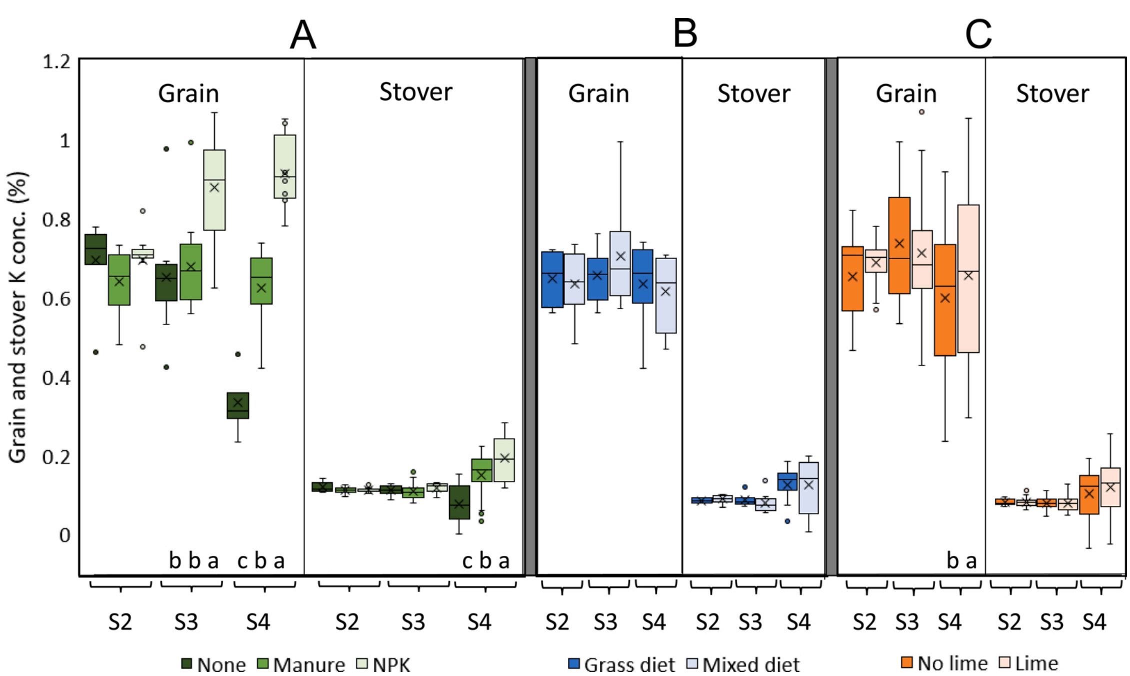

Fig. 8. Main effects of (A) fertiliser and cattle manure, (B) manure type and (C) liming with travertine on potassium (K) concentration in maize grain and stover. Effects of nutrient input (NPK vs manure vs none; mixed-diet manure vs grass-diet manure) and liming (limed vs non-limed) were tested in a two-factorial approach and means are indicated by '×' inside the boxes. 'Manure' in (A) is the average of both types of manure. Parameters are clustered with brackets according to growing seasons 2 to 4 (S2-S4). LSMeans within each cluster marked with different letters are significantly different ($p < 0.05$).

diet manure. However, in season 4, the stover N concentration was higher in the crop receiving mixed-diet manure than in that receiving the grass-diet manure (Fig. 6B). In seasons 2 and 4, grain P concentration was highest in the crop receiving mixed-diet manure (Figs. 7B). Liming generally increased the nutrient concentrations during season 4 (Figs. 6–8C).

3.5. Relationship between maize composition and yield

Most of the variation in maize grain yield was explained by the stover yield, with some further explanation of the variation provided by the grain N and P concentrations (Table 3). The significant correlation with grain N concentration was, however, only evident when tested across all seasons. Stover yield was, in turn, mainly explained by its P

Table 3
Correlations of maize grain yield with stover yield and nitrogen (N), phosphorus (P) and potassium (K) concentrations in grain and stover, and correlation of stover yield with stover N, P and K concentrations. n = 96.

	Grain yield			Stover yield		
	Coeff.	p value	Partial R^2	Coeff.	p value	Partial R^2
Stover yield	0.80	<0.0001	0.81	-*	–	–
Grain N	0.12	0.010	0.01	–	–	–
Grain P	0.14	0.004	0.02	–	–	–
Grain K	ns	ns	ns	–	–	–
Stover N	−0.12	0.013	0.01	−0.27	<0.0001	0.08
Stover P	ns	ns	ns	0.71	<0.0001	0.61
Stover K	ns	ns	ns	ns	ns	ns
Model R^2			0.85			0.69

* '-' indicates not included in tests.

concentration (Table 3), and this was significant for each season separately (coeff. = 0.60/0.54/0.37; p < 0.001 for all; partial R^2 = 60/66/66 for seasons 2, 3 and 4, respectively). There was a weaker negative correlation with its N concentration when tested across all seasons (Table 3), but the correlation was positive in season 4 (coeff. = 0.27; p = 0.001; partial R^2 = 0.10).

3.6. Nutrient removal by the crop

The amounts of nutrients in aboveground maize biomass varied greatly. For example, the ranges were 18–146 kg N ha^{-1}, 6–33 kg P ha^{-1} and 11–111 kg K ha^{-1} in season 4, with the highest amounts in the NPK treatments and the lowest in the unfertilised controls (Figs. 9–11A). The effect of the two manure types on the N, P and K content in aboveground maize biomass generally did not differ, except in season 4 when the amounts of N and P tended to be higher after mixed-diet manure application (Figs. 9–10B). Liming generally did not significantly affect the amounts of N, P and K contained in the biomass in seasons 2 and 3, but increased the amounts in season 4 (Figs. 9–11C).

4. Discussion

Low water availability clearly limited crop growth in seasons 1–3, when yields ranged from zero (i.e. complete crop failure, in all treatments) to 2.6 t ha^{-1}. In season 4, the total water supply (rainfall and supplementary irrigation) was 560 mm, compared with 450 and 440 mm in seasons 2 and 3, respectively. In season 4, maize yield reached 7.2

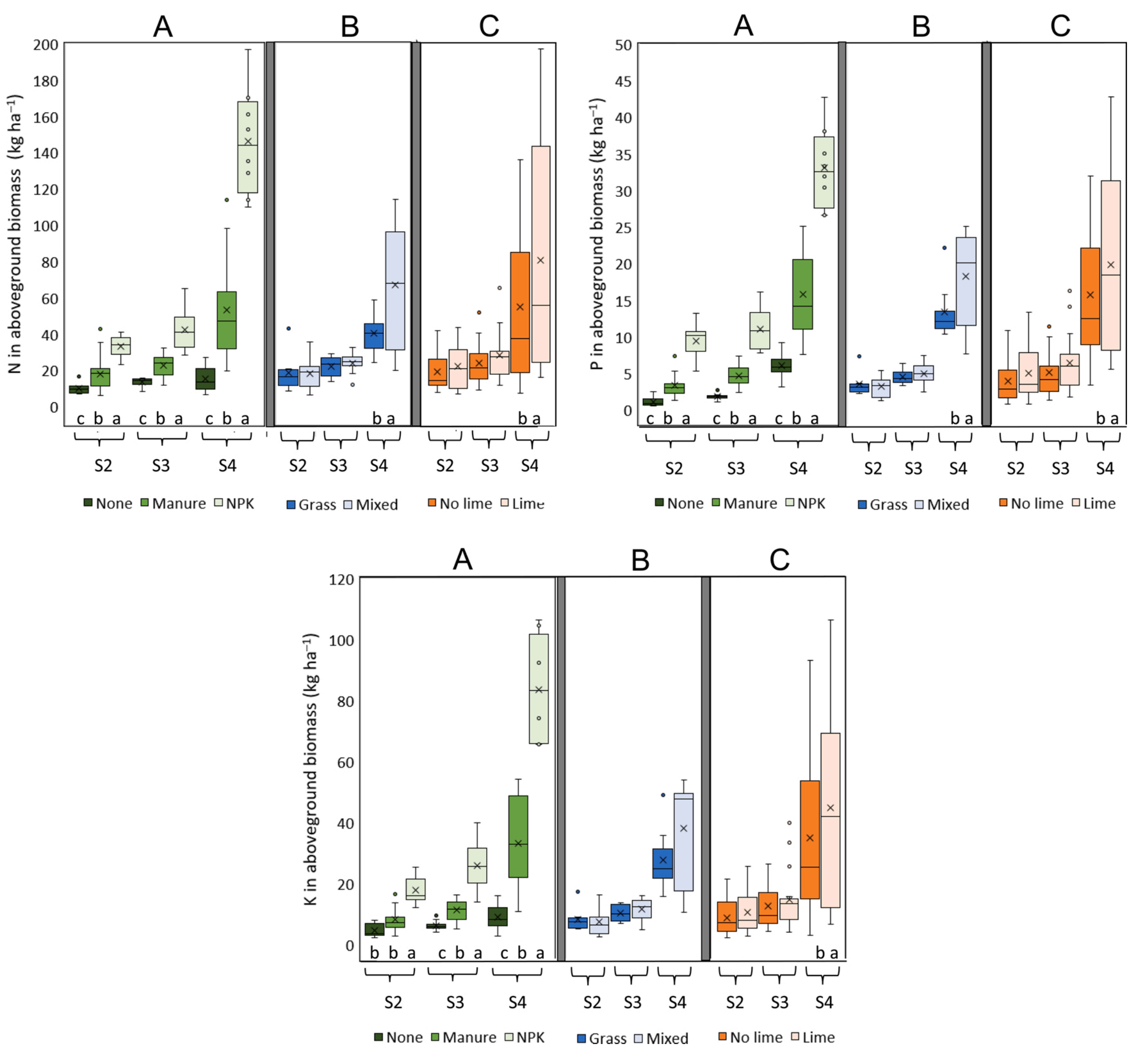

Fig. 9–11. Main effects of (A) fertiliser and cattle manure, (B) manure type and (C) liming with travertine on the amounts of nitrogen (N, Fig. 9), phosphorus (P, Fig. 10) and potassium (K, Fig. 11) in aboveground parts of the maize crop. Effects of nutrient input (NPK vs manure vs none; mixed-diet manure vs grass-diet manure) and liming (limed vs non-limed) were tested in a two-factorial approach and means are indicated by '×' inside the boxes. 'Manure' in (A) is the average of both types of manure. Parameters are clustered with brackets according to growing seasons 2 to 4 (S2-S4). LSMeans within each cluster marked with different letters are significantly different (p < 0.05).

t ha^{-1} in the limed NPK treatment, suggesting that water limitation was of less importance than in the preceding seasons.

4.1. Nutrient limitations to crop growth

Grain yield was most closely correlated with stover yield, which explained 81 % of the variation in grain yield in spite of the variation in harvest index. Stover yield in turn was most strongly correlated with its P concentration, which explained 61 % of the variation in stover yield, indicating that crop P availability was generally the most limiting of the nutrients included in the analysis. The P concentrations in stover were very low during seasons 2 and 3, with an average across treatments of 0.08 % in both seasons. These are comparable to the lowest values found in maize shoots at crop maturity by Jones (1983) and close to the average P concentrations in maize stover reported by Sanginga and Woomer (2009). While the concentrations during season 4 were still very low in the unfertilised controls, the P levels in the NPK and manure treatments were somewhat higher, and were accompanied by a positive and significant correlation between stover N concentration and yield. This suggests that, in contrast to seasons 2 and 3, N may have been a limiting nutrient in season 4 because of enhanced P nutrition.

4.2. Response to fertilization

Low-fertility soils frequently exhibit a low crop response to fertilisation, i.e. are so-called non-responsive, which may be due to deficiencies of nutrients other than those applied, soil acidity and/or poor soil physical properties such as low water-holding capacity and low porosity, leading to low water infiltration and drainage rates (Vanlauwe et al., 2010b; Kihara et al., 2016). The low pH and generally low nutrient concentrations at the site used in the present study (Mukangango et al., 2020) suggest that the soil at the site may be non-responsive (Assenga et al., 2016). However, the increase in maize yield observed upon NPK fertilisation compared with the unfertilised control shows that the soil at the experimental site was responsive to fertiliser application. In fact, plots receiving mineral NPK fertiliser at a rate of 70 kg N ha^{-1} produced yields of around 7 t ha^{-1} during season 4, suggesting that other nutrients in the soil were present in sufficient availability for crop needs at least during the three growing seasons for which yield data were obtained (seasons 2–4). This was supported by the absence of visible symptoms of e.g. S, Mg or Zn deficiency. However, the soil had been under fallow for more than 10 years prior to establishment of the experiment, which may have allowed a build-up of multiple nutrients. If future inputs are restricted to N, P and K, the availability of other nutrients will most likely decline and in the longer term limit the response to NPK inputs. The increase in maize yield achieved through NPK fertilisation will also increase nutrient exports with the produce. Tovihoudji et al. (2017) showed a risk of accelerated N, P and K mining with micro-dosing of fertiliser and there may be an even higher risk of mining of nutrients that are not applied. This underpins the value of combined application of mineral fertilisers and organic inputs for long-term soil fertility.

The high yield of the NPK treatments in season 4 and the enhanced N concentration in the maize showed that crop N uptake (corresponding to 146 kg N ha^{-1}) was higher than the sum of N applied (70 kg N ha^{-1}) and N mineralised from the soil pool (20 kg N ha^{-1} in the unfertilised treatments). This suggests that residual fertiliser N was present in the soil from growing seasons 2 and 3, due to previously low production connected with low or poorly distributed rainfall. Residual nutrients are at risk of being lost, in the case of N through leaching and gaseous losses. These constitute an economic loss to farmers and, as fertiliser use increases, a risk of eutrophication of surrounding aquatic environments. Soil analysis before crop establishment would allow the fertiliser rate to be adjusted to achieve a target level of nutrient availability and increase nutrient use efficiency. This would require soil analysis services to be known, available and affordable to smallholder farmers.

4.3. Crop response to manure application

Cattle manure on smallholder farms in SSA is frequently characterised by low nutrient concentrations (Mugwira and Mukurumbira, 1986; Lekasi et al., 2002; Sileshi et al., 2017) and slow nutrient release (Murwira and Kirchmann, 1993). These characteristics reflect low fodder quality and considerable losses of nutrients, especially N, during manure handling and storage (Nzuma and Murwira, 2000). Hence, application of cattle manure may need to be repeated for several growing seasons before yields increase significantly (e.g. Nyamangara et al., 2005). Due to the failure of the crop in season 1, we were unable to evaluate the effect of manure application that season. However, maize yield increased significantly from season 2, suggesting a relatively rapid nutrient supply from the manure (consistent with the C:N ratios of 13–14) and also enhanced soil organic C concentrations and soil physical properties reported by Mukangango et al. (2020). As a result of frequent collection and covered storage of the manure, the concentrations of N and P in the manures used in this study were at the higher end of the ranges reported by Lekasi et al. (2002). Although high frequency of collection may be difficult to maintain on smallholder farms, manure storage in a lined and covered pit should be feasible for a considerable proportion of smallholder farmers. The application rate tested (5 t ha^{-1}) should also be feasible on a substantial proportion of the land of many farms. Around 25 % of Rwandan farm households have at least one cow (from the “One cow per poor family program”) and manure production from the local cattle breed (Ankole) is estimated to be 6 t $head^{-1}$ yr^{-1} (Kim et al., 2013), while improved breeds may produce more manure. With an average farm size in Rwanda of around 0.5 ha, the manure from only one stall-fed animal can thus make an important contribution to meeting crop nutrient inputs.

The SPAD meter readings used to monitor leaf chlorophyll content (and thus N status) showed values of 32–50 at tasselling, which is within the ranges reported by Buchaillot et al. (2019) and Munialo et al. (2019). The lowest values in this study were close to the lowest value recorded by Munialo et al. (SPAD reading 38) after application of 34 kg N ha^{-1}. This suggests that the N supplying capacity of the soil at our study site in Rwanda was reasonable, which was confirmed by the plant N content in the unfertilised control in season 4 (18 kg). The highest SPAD readings and yield were, as expected, found in the NPK treatment. However, considering that N and P in the manure were partially in the organic fraction, and that the manure dose was only 5 t DM ha^{-1} (25 % of recommended dose), the maize yield increase in the manure treatment was remarkable.

Enhanced soil organic C content, water-holding capacity and water infiltration rate at maize planting holes (Mukangango et al., 2020) may have decreased water runoff on the terraces during high-intensity rainfall and increased crop water supply over the growing season, which may have contributed to the yield response of the manure treatments. Season 2 experienced very low rainfall (167 mm), while season 3 had somewhat higher rainfall (238 mm) but a two-week dry spell early in the season. Season 4 had rainfall of 409 mm, but still experienced several one-week intervals without precipitation. Soils with slow water infiltration and low water-holding capacity are increasingly challenging in rain-fed cropping systems experiencing high climate variability. Where insufficient manure availability precludes sufficient application rates to achieve improved soil properties on a wider scale, applying reduced manure rates only to planting holes may be a way to enhance the rooting environment, water supply and survival of young crop plants and retain higher crop density on fields (Fatondji et al., 2006). Many studies have reported increased cereal crop yields following micro-dosing of inorganic fertiliser (e.g. Aune et al., 2007; Hayashi et al., 2008; Bagayoko et al., 2011; Camara et al., 2013). The effects of applying reduced manure rates only to planting holes have been less well studied, and we did not specifically test the application technology in the present study. However, the increased maize growth and yield in response to manure application found here agree with findings by

Mugwira et al. (2002) that small amounts of manure applied to the planting holes are efficient in raising maize yield. Ibrahim et al. (2016) reported a positive effect of manure application to planting holes compared with broadcasting when it was combined with micro-dosed inorganic fertiliser. The observed yield increase in that case was accompanied by enhanced lateral root development and higher water use efficiency, suggesting improved plant scavenging capacity for nutrients and water (Ibrahim et al., 2016).

4.4. Differences between manure types

Manure quality in terms of N and base cation concentrations was enhanced by the mixed diet including *A. angustissima*, corroborating earlier findings on increased manure N concentrations by e.g. Lekasi et al. (2002) and Muinga et al. (2007). Our results also corroborate findings by Saha et al. (2008) of similar P concentrations in goat manure after a basal grass diet and supplementation with foliage from three legume tree species, but contradict their findings of no difference in manure K concentrations.

The change in manure quality did not significantly increase yields during seasons 2 and 3. However, it increased yield and N and P content of aboveground biomass during season 4, suggesting a benefit from the improved manure quality in the longer term. It can be assumed that farmers' main objective in introducing legumes to the diet of their animals is to increase animal productivity, but enhanced fertiliser effect of the resulting manure may be a positive side-effect, especially if the elevated N concentrations in animal faeces and urine can be retained in the manure during handling and storage, as discussed above.

4.5. Response to liming

Maize is generally considered to suffer from soil pH below 5.5 (Lidon and Barreiro, 2002; Sirikare et al., 2015). The Handbook for Integrated Soil Fertility Management issued by the Africa Soil Health Consortium suggests that liming of soils may be needed at pH_{H2O} <4.5 (Bationo et al., 2012). The small and only occasionally significant difference in maize yield observed between limed and non-limed treatments in the present study suggests, somewhat surprisingly, that soil pH (baseline value 4.2) was not a major limiting factor for the maize variety used in the experiment or that the pH increase over the study period (to maximum pH 5.2 in the limed mixed-diet manure treatment; Mukangango et al., 2020) was not sufficient to significantly increase crop performance. However, some maize varieties are known to exhibit tolerance to soil acidity (Evans et al., 2013) and a different maize variety than that used in the study may have been more affected by the low pH and may have shown a clearer response to the pH change. Nevertheless, although the effect of liming on maize yield was only occasionally significant, the increase in maize nutrient concentrations suggests somewhat enhanced nutrient availability and/or root function.

Soil pH was found to increase in the experiment due to manure application as well as liming (Mukangango et al., 2020), agreeing with former findings by e.g. Mucheru-Muna et al. (2014). Further to a potential effect on the crop by the pH increase *per se*, Naramabuye and Haynes (2007) have demonstrated that exchangeable Al^{3+} can be complexed with soluble organic matter, leading to a decrease in crop Al^{3+} exposure. Nevertheless, due to the low response to liming, the capacity of the manure to affect maize performance and yield via raised pH was not strongly tested in the present study.

5. Conclusions

In this four-season study in Rwanda, the highest maize yields were attained with NPK fertiliser applied to the planting holes. Manure applied to the planting holes, at approximately the same total N rate as the NPK fertiliser, produced significantly higher grain and stover yields than the unfertilised control, but lower than the fertiliser treatment. Manure produced from cattle fed a mixed grass-legume diet produced higher grain yield during growing season 4 compared with manure from cattle fed grass only. The amount of manure applied at reduced rate to the planting holes (5 ton DM ha^{-1} $year^{-1}$) may well be achievable for farmers who stall-feed their livestock on smallholdings. If smallholder farmers can supplement livestock diets with e.g. suitable legume tree foliage and improve manure storage practices, there is thus scope for enhanced farm productivity despite low cash availability for mineral fertiliser purchase.

CRediT authorship contribution statement

A. Sigrun Dahlin: Conceptualization, Formal analysis, Methodology, Project administration, Resources, Supervision, Writing - original draft, Writing - review & editing. **Marguerite Mukangango:** Conceptualization, Investigation, Methodology, Project administration, Writing - review & editing. **Francois Xavier Naramabuye:** Methodology, Resources, Supervision, Writing - review & editing. **Jean Nduwamungu:** Methodology, Supervision, Writing - review & editing. **Gert Nyberg:** Methodology, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors report no declarations of interest.

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