

Full Length Research Paper

Nitrogen value of stockpiled cattle manure for crop production

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Cattle manure is a common source of fertilizer throughout Sub-Saharan Africa given problems with supply and pricing of inorganic fertilizers. The optimum rate of manure to use is often unknown and further compounded by variable N contents arising from long periods of stockpiling. This study investigated the rates of cattle manure required to optimize plant growth at different N contents arising from different storage times. A field experiment was established using cattle manure stored in the open for 4, 12 and 13 months (N content of 1.31, 1.18 and 0.32%, respectively). Plant shoot dry weight and N uptake of canola (*Brassica napus* L) was compared to equivalent rates of inorganic N (urea) to 200 kg N ha⁻¹ at two sampling points over two growing seasons. Linear models of the form $y = a + bx$ were fitted to the data where y is yield (dry matter or N uptake) to enable the N equivalent value (NEV) of cattle manure treatments to be compared to inorganic fertilizer. The NEV of cattle manure stored for 4 months averaged 30% for shoot dry weight and 24% for N uptake and decreased with storage. Impractical volumes of cattle manure are required for plant production in aged stockpiles, thus necessitating better options for N management.

Key words: Sub-Saharan Africa, cattle manure, nitrogen fertilizer, N equivalent value, stockpiled manure.

INTRODUCTION

Nitrogen deficiency is among the top five factors limiting soil fertility in Sub-Saharan Africa (SSA) (Stewart et al., 2020). Studies by Muhereza et al. (2014) identified N as the limiting soil macro-nutrient for many farmers in peri-urban Uganda. The application of inorganic fertilizer by smallholder farmers in SSA to improve soil nutrient levels is low compared to world standards (Sheahan and Barret, 2014; Kaizzi et al., 2017). Numerous economic factors

such as price policies and credit, distribution costs, the privatization of supply, and infrastructural development contribute to the low availability and use of inorganic fertiliser (Mwangi, 1996; Croppenstedt et al., 2003). Instead, cattle manure is commonly used by smallholder farmers to improve crop growth (Ndambi et al., 2019). It is usual practice for cattle manure to be stored in piles for periods of between 2 to 6 months to

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Table 1. Percentage Nitrogen (N) content and N equivalent values (NEV) for a range of cattle manures and crop responses compared to inorganic N in the first year of application.

Manure type	N Content %	Crop	NEV%	Reference
Solid FYM	0.8	Silage	4-32	Chambers et al. (1999)
Solid manure	1.6	Corn	10-50	Gale et al. (2006)
Solid manure	0.7	Silage	35	Ferguson et al. (2005)
Solid manure	0.5	Barley and potato	46-59	Mallory et al. (2010)

bulk up adequate manure for the crop prior to application. The manure is sourced from farmers that practice animal confinement and manure storage (Muhereza, 2011; Katuromunda et al., 2012).

There are limited studies available to determine the volume of cattle manure required to supply adequate nutrients for crop growth, particularly where stockpiled over long periods of time. The nutrient content of cattle manure varies and is affected by various factors such as the type of livestock (Griffin et al., 2002; Esfahani et al., 2016), age, diet, the inclusion of bedding material, the duration and conditions of storage and the kind of treatment prior to soil application (Reijs et al., 2007; Snijders et al., 2013; Leip et al., 2019). The N content in cattle manure in SSA is low in N compared to elsewhere and is attributed to poor handling, collection and storage of manure, insufficient fodder and poor livestock diet. For example, values of 0.56% N have been measured in fresh manure in Uganda, with declines to 0.44% N in uncovered manure and 0.42% in aged manure (Muhereza, 2011). The N Equivalent Value (NEV) calculates the equivalent amount of N in manure required to give similar plant yield at comparable rates of inorganic N. Table 1 shows that the NEV for cattle manures (N content from 0.5 to 2.1%) varies considerably from 0 to 59% in the first year of application compared to inorganic fertilizer N. The type of manure, for example solid manure, composted manure or fresh manure is responsible for much of this variation (Table 1).

Therefore, to better improve soil fertility and optimize food production where cattle manure is used as a source of fertilizer in SSA, research is required to determine effective rates of manure required following stockpiling for different lengths of time. This research aims to determine the effect of stockpiling of cattle manure on its value as a source of N. These search outcomes will better guide manure application rates and storage options and is relevant to developing countries with similar farming systems with limited access to fertilizer N.

MATERIALS AND METHODS

Experimental design

A field experiment was established over two growing seasons

(2009 and 2010) using three sources of stockpiled cattle manure, comprising manure stored in the open for 4, 12 and 13 months; designated as M₄, M₁₂ and M₁₃, respectively. The manure was sourced from a feedlot where cattle had been fed a maintenance diet of pelletised hay and grain. The stored manure was of low quality to reflect manure commonly available to farmers in SSA. The concentration of total N in the stockpiled manure decreased with storage time, ranging from 1.31 to 0.32% (Table 2).

The 2009 experiment comprised 12 treatments; six (6) rates of stockpiled M₁₃ cattle manure (0.32% total N) and 6 rates of inorganic N fertilizer. The 2010 experiment comprised 18 treatments; 6 rates of stockpiled M₄ cattle manure (1.31% total N), six (6) rates of stockpiled M₁₂ cattle manure (1.18% total N) and 6 rates of inorganic N fertilizer (Table 2). The rates of inorganic N applied as urea (46% total N) up to 214 kg N ha⁻¹ were selected to apply similar amounts of N to manure treatments (Table 3). All treatments included three replications to give a total of 36 plots in 2009 and 54 plots in 2010. Plots measuring 2m x 2m and were arranged in a systematic gradient design to prevent edge effects that may result from a high rate plot adjacent to a low rate plot as per Rigby (2008). The elimination of wide guard rows facilitated an increased number of fertilizer rates, increased the ratio of harvested to non-harvested area and reduced the potential threats from experimental error.

Location and soil type

The field experiments were established at Ucarty, located 120km east of Perth, Western Australia (-31.19159°S, 116.57083°E) on a dark yellowish-brown sand (Table 4). The region experiences a dry temperate climate with cool, wet winters and hot, dry summers, and an average rainfall of 302 mm over the growing season (April-October). The site was chosen to be low in N to enable a nutrient response to be determined.

Application of manure and basal nutrients

To ensure that all plant nutrient requirements were adequate other than N, basal nutrients were broadcast by hand to the site prior to planting and then incorporated by disc plough working across plots; 0.04 kg P ha⁻¹ (superphosphate 9 kg ha⁻¹), 0.24 kg K ha⁻¹ (muriate of potash 588 kg ha⁻¹), 0.003kg Cu kg ha⁻¹ (copper sulphate 6.7 kg ha⁻¹), 0.005 kg Zn ha⁻¹ (zinc sulphate 13.3 kg ha⁻¹), 0.01 kg CaSO₄·2H₂O ha⁻¹ (gypsum 12.5 kg ha⁻¹) and 0.05 kg Mnha⁻¹ (manganese sulphate 120 kg ha⁻¹). Cattle manure was weighed into buckets using an electronic weighing scale, broadcast evenly by hand onto respective plots, and then incorporated into the soil during seeding by discs. Inorganic N was broadcast by hand onto the respective plots and split over two applications at seeding and at 8 weeks after planting, a common practice in the region. The first application was incorporated at seeding by discs and the second

Table 2. Total percentage of nitrogen (N) in the three stockpiled cattle manures used in the study.

Analysis	Type of cattle manure		
	M ₄	M ₁₂	M ₁₃
Dry matter content			
Total N (%)	1.31	1.18	0.32

Western Australian ChemCentre report # 09A0508:5. National Association of Testing Authorities - NATA accredited. Analysis measured on sub-samples at a depth of 45 cm from the surface of the stockpile. Cattle manure oven dried at 105°C in a forced air oven and reported as 90% dry basis, mg kg⁻¹. Total N by combustion. Nitrate-N and ammonium-N measured by SFA and less than 0.04 mg kg⁻¹ in all samples. Other constituents in M₁₃ as follows: pH 7 (0.01M CaCl₂; 1:5), organic carbon 6.7%W/B, 0.11 mg total P kg⁻¹.

Table 3. Target rates of N (kg ha⁻¹) and equivalent quantities of cattle manures (kg plot⁻¹) at three stockpile months applied in the study.

Target rate N (kg ha ⁻¹)	M ₄ (kg plot ⁻¹)	M ₁₂ (kg plot ⁻¹)	M ₁₃ (kg plot ⁻¹)
0	0	0	0
40	3.0	3.4	12.5
86	6.1	6.8	26.8
128	9.2	10.2	40.0
170	12.2	13.6	53.2
214	15.3	16.9	66.8

Cattle manure rates calculated at a DM of 90%.

Table 4. Selected soil characteristics of the <2 mm fraction of the top soil (0-10 cm) at the study site.

Parameter	Value
pH (0.01 M CaCl ₂ ; 1:5)	5.0
EC (1:5) (mS/m)	6.0
Sand (%)	95.5
Silt (%)	2.0
Clay (%)	2.5
Organic C (%W/B)	0.74
Total N (%)	0.065
Total P (mg/kg)	74.0
P (HCO ₃ Colwell) (mg/kg) I	7.0
K (HCO ₃ Colwell) (mg/kg)	45.0

Western Australian ChemCentre WA Report 08A7/1-5 (National Association of Testing Authorities - NATA accredited) (n = 4). Values averaged from four random 5 cm diameter soil cores bulked and then dried at 40°C for 72 h in a forced air oven.

application was top dressed only.

Seeding and site management

Canola (*Brassica napus* L) is efficient at capturing high amounts of N during vegetative growth (Kazemeini et al., 2010). It was suitable

for the dryland temperate climate of the study site and is from a similar family to cabbage (*Brassica oleracea*), a staple food crop in Uganda. Canola has similar early plant growth and N uptake to canola (Muhereza, 2011). Canola was sown at the start of each growing season at a rate of 9 kg ha⁻¹ by top dressing by hand and incorporating to a maximum depth of 4 cm by a disc seeder. Weeds were controlled by spraying with glyphosate (2 L ha⁻¹) prior to

planting and Amor (150 mL ha⁻¹) for grass control five weeks after planting and by hand weeding on sampling days. An electric fence was erected to prevent cattle and field rabbits from damaging the crop. Weather data (maximum, minimum and average) was recorded by an automated weather station.

Plant growth measurements and nitrogen uptake

Whole plant (above ground) samples of canola were collected from 0.25 m² quadrants of each plot at 63 days after sowing (DAS) and 93 DAS in 2009 and 70 DAS and 100 DAS in 2010. Plant tissue was dried to a constant mass at 70°C for 48 h in a forced-air oven to determine dry matter (DM). The average plant density per plot was determined at the first sampling date. The dried plant samples (g m⁻²) were then used to determine concentration of total N in shoots by combustion in a Leco FP-428 analyser. Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) was used to determine concentrations of other plant nutrients; P, K, Ca, Mg, Na, S, Fe, Mn, Zn, and Cu (CCWA, 2000). Nitrogen uptake by canola was determined by multiplying the shoot DM yields with the N concentration.

Data analysis

Statistical analysis of data was carried out using standard analysis of variance (ANOVA) (Gen Stat Procedure Library Release PL20.1) (Payne et al., 2011). The significance of the treatment effect was determined using the F-test, while the least significant differences (LSD) between the means of the six treatments were estimated at the 5% probability level to determine if cattle manure had a significant effect on crop growth and yield compared with inorganic fertilizer.

Dry matter yields and N uptake in cattle manure were analysed by linear regression analysis and compared to respective yields from mineral N calibration plots using models of the form $y = a + bx$ where y is the yield (kg ha⁻¹ DM or N uptake). The quadratic equations of the form ($y = a + bx + cx^2$) was tested for the data but the crop response did not approach a curvilinear at the top rates of application and the quadratic term (x^2) in the crop response model was not significant at $P < 0.05$. Hence linear regression was considered the most appropriate to use in this study, particularly as yield response to manure N is considered linear between applications of 0-300 kg N ha⁻¹ (Whitehead, 1995). Where the linear regression was significant according to ANOVA analysis, NEV were obtained by comparing the slopes of the regression equations for N from cattle manure to the slope obtained for inorganic N for both DM yield and N uptake.

RESULTS

Weather

The growing season rainfall (May to October) at the study site received 246 mm in 2009 and 237 mm in 2010. Rainfall in both years of the experiment was relatively low compared to the long-term average of 302 mm, with low out of season rainfall experienced between the two years.

Canola dry matter yield

The DM yield of canola shoots increased with increasing rates of inorganic-N at all sampling dates for both

seasons (Figure 1). Inorganic-N treatment at 200 kg N ha⁻¹ reached a maximum yield of 2,582 kg DM ha⁻¹ during the first season (2009) at 93 DAS and 1,400 kg DM ha⁻¹ during the second season (2010) at 100 DAS. At all N rates and sampling dates, the application of inorganic-N resulted in higher yields compared to all sources of cattle manure-N at equivalent application of N ($P < 0.001$). There were large increases in DM yield for inorganic-N between the rates of 40 kg N and 80 kg N ha⁻¹.

In cattle manure stockpiled for 13 months (M₁₃), the maximum DM yield of canola at 63 DAS was 190 kg ha⁻¹ at the highest N application rate (214 kg N ha⁻¹) and increased to 631 kg ha⁻¹ at 93 DAS (Figure 1). Shoot DM yields averaged 4 times less than equivalent inorganic-N over the growing season. In cattle manure stockpiled for 12 months (M₁₂), the maximum DM yield of canola at 70 DAS was 80 kg ha⁻¹ at the highest N application rate and increased to 537 kg ha⁻¹ at 100 DAS (Figure 2). Shoot DM yields averaged 3 times less than equivalent inorganic N over the growing season. In cattle manure stockpiled for 4 months (M₄), the maximum DM yield of canola at 70 DAS was 110 kg ha⁻¹ at highest N application rate and increased to 260 kg ha⁻¹ at 100 DAS (Figure 2). The DM yield of canola in equivalent rates of inorganic-N was 600 kg ha⁻¹ at 70 DAS and increased to 1,436 kg ha⁻¹ at 100 DAS. Compared to equivalent rates of inorganic-N, shoot DM yields were reduced from 2.3 to 2.4 times less over the growing season.

Shoot nitrogen concentration and uptake

The concentration of N in the DM of canola shoots was positive to increasing rates of N (data not given). Over both growing seasons (2009 and 2010), shoot N concentrations declined overtime with overall means as follows; 3.2 to 2.8% from 63 to 93 DAS and 3.4 to 2.6% from 70 to 100 DAS, respectively. Mean total N uptake by canola shoots increased with increasing rates of either inorganic N or cattle manure N (M₄, M₁₂ and M₁₃) at all sampling dates (Tables 4 and 5). The highest values of N uptake (kg ha⁻¹) were in the inorganic-N fertilizer treatments and ranged between 1.2 and 14.0 kg N ha⁻¹ at the first sampling and between 5.0 and 54.5 kg ha⁻¹ at the second sampling time as rates of N increased from 0 to 120 kg ha⁻¹. As the storage time of manure increased, the total N uptake by canola decreased, with manure stored for 13 months having the lowest N uptake compared to all other treatments at both sampling dates. There were significant differences ($P < 0.001$) in N uptake between inorganic-N and cattle manure-N at comparable total N loadings at both sampling dates.

Stockpiled cattle manure-N compared with inorganic-N during the growing season

Nitrogen equivalent values (NEV) of stockpiled cattle

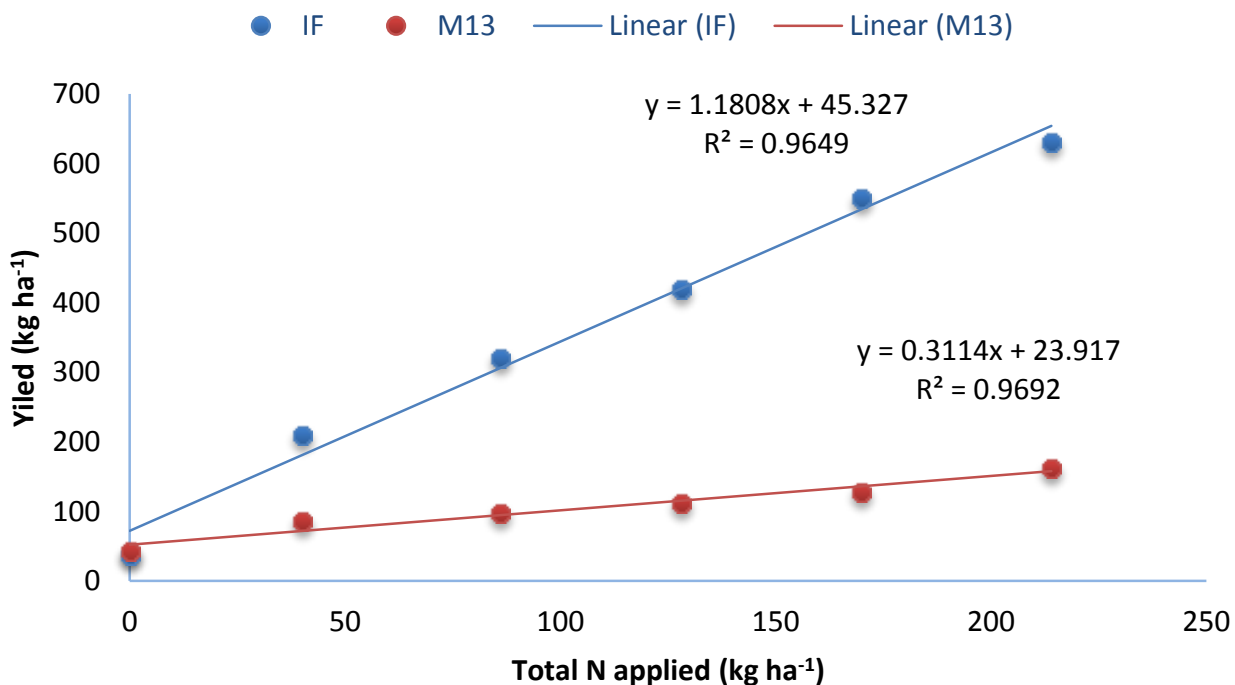


Figure 1. Mean vegetative dry matter yield (kg ha⁻¹) in relation to rate of total N application in inorganic-N (urea), cattle manure-N stored for 13 months (M₁₃) at 63 DAS with regression equation and standard error bars given. Values are the means of three replicates. Line plotted using Microsoft Excel. Vertical bars denote LSD (P = 0.05) for data from all treatment means.

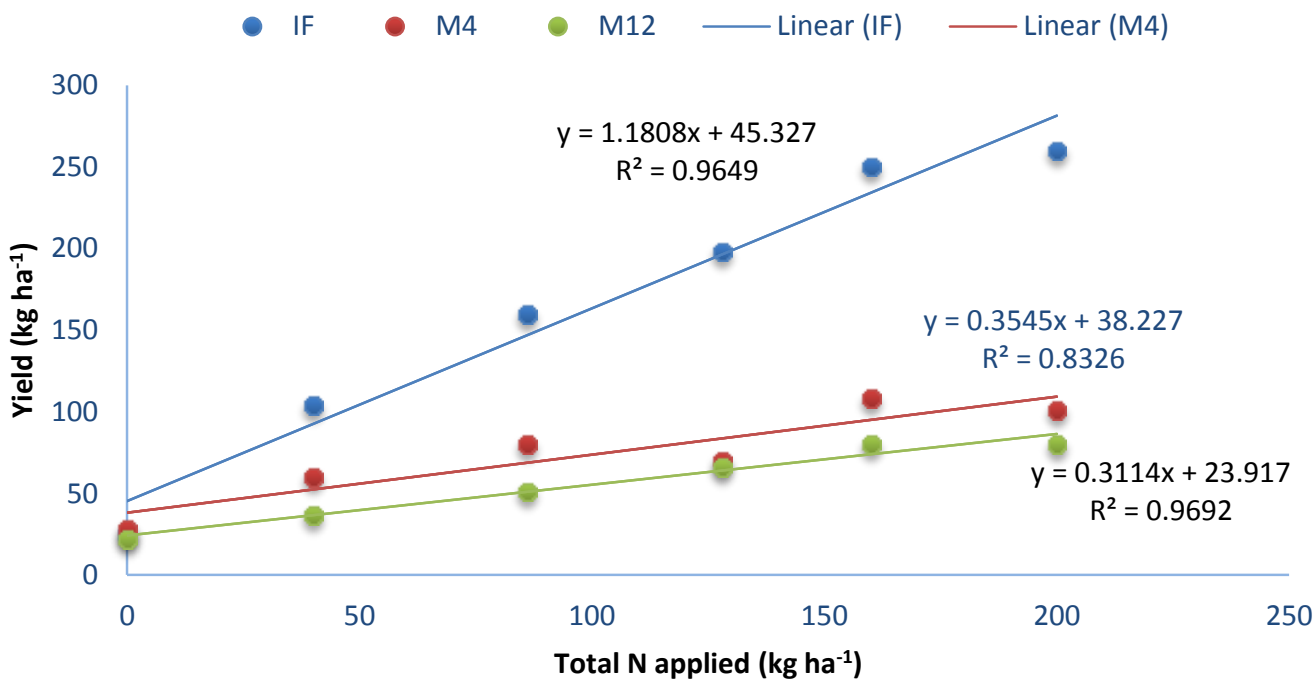


Figure 2. Mean vegetative dry matter yield (kg ha⁻¹) of canola in relation to rate of total N application in inorganic-N (urea), cattle manure-N stored for 4 months (M₄) and 12 months (M₁₂) at 70 DAS in 2010 with regression equation and standard error bars given. Values are the means of three replicates. Line plotted using Microsoft Excel. Vertical bars denote LSD (P = 0.05) for data from all treatment means.

Table 5. Mean total N uptake (kg ha^{-1}) in canola shoots in relation to equivalent levels of N applied in inorganic fertilizer (IF) and stockpiled cattle manure at the first sampling period (between 63 and 70 DAS).

Source	N Rate (kg ha^{-1})					
	0	40	80	120	160	200
M ₄	1.1	1.8	2.4	3.0	3.1	3.8
M ₁₂	1.2	1.7	1.8	2.3	2.7	2.7
M ₁₃	0.9	1.5	1.5	1.8	2.1	2.2
IF	1.2	3.4	6.6	8.7	11.1	14.0

M₄: manure stored for four months (63 DAS); M₁₂: manure stored for twelve months (70 DAS); M₁₃: manure stored for thirteen months (70 DAS); IF: inorganic N fertilizer.

Table 6. Mean Total N uptake (kg ha^{-1}) in canola shoots in relation to equivalent levels of N applied in inorganic fertilizer (IF) and stockpiled cattle manure at the second sampling period (between 93 to 100 DAS).

Source	N Rate (kg ha^{-1})					
	0	40	80	120	160	200
M ₄	5.0	8.1	8.7	11.3	16.2	18.7
M ₁₂	5.0	8.2	10.3	9.9	13.2	15.9
M ₁₃	4.0	6.5	8.0	9.2	11.4	13.0
IF	5.0	15.5	24.0	31.9	40.3	54.5

M₄: manure stored for four months (93 DAS); M₁₂: manure stored for twelve months (100 DAS); M₁₃: manure stored for thirteen months (100 DAS); IF: inorganic N fertilizer.

Table 7. Linear regression coefficients and r^2 values for DM yield and N uptake in canola in stockpiled cattle manure-N (M₄, M₁₂ and M₁₃) and inorganic-N fertilizer (IF) at the first sampling times of 63 DAS (2009) or 70 DAS (2010).

Source	Dry weight				N Uptake			
	63 DAS		70 DAS		63 DAS		70 DAS	
	Slope	r^2	Slope	r^2	Slope	r^2	Slope	r^2
M ₄	-	-	0.307	0.64	-	-	0.013	0.69
M ₁₂	-	-	0.216	0.49	-	-	0.072	0.45
M ₁₃	0.497	0.91	-	-	0.017	0.52	-	-
IF	3.036	0.98	1.117	0.74	0.127	0.85	0.064	0.81

M₄: manure stored for four months; M₁₂: manure stored for twelve months; M₁₃: manure stored for thirteen months, IF: inorganic N fertilizer.

Table 8. Linear regression coefficients and r^2 values for DM yield and N uptake in canola in stockpiled cattle manure-N (M₄, M₁₂ and M₁₃) and inorganic-N fertilizer (IF) at the second sampling time of 93 DAS (2009) or 100 DAS (2010).

Source	Dry weight				N Uptake			
	93 DAS 2009		100 DAS 2010		93 DAS 2009		100 DAS 2010	
	Slope	r^2	Slope	r^2	Slope	r^2	Slope	r^2
M ₄	-	-	1.99	0.63	-	-	0.07	0.68
M ₁₂	-	-	1.54	0.71	-	-	0.05	0.64
M ₁₃	2.29	0.86	-	-	0.06	0.69	-	-
IF	10.41	0.94	6.03	0.89	0.35	0.86	0.24	0.88

M₄: manure stored for four months; M₁₂: manure stored for twelve months; M₁₃: manure stored for thirteen months, IF: inorganic N fertilizer.

manure compared with inorganic-N fertilizer for each measure of crop response (DM yield and N uptake) demonstrated a significant relationship between rates of

N application ($P < 0.05$) (Tables 7 and 8). The fitted model accounted for 64 to 98% of the variance of the experimentally derived results for DM at the first sampling

Table 9. Nitrogen equivalent values (NEV) of stockpiled cattle manure for DM yield (kg ha^{-1}) and N uptake (kg ha^{-1}) of canola on comparison of linear regression coefficients with inorganic-N fertilizer at two sampling dates for the two years.

Source	Total N (%)	DAS	Year	Dry matter (kg ha^{-1})	N uptake (kg ha^{-1})
M ₄	1.31	70	2010	0.27	0.20
M ₁₂	1.18	70	2010	0.19	0.11
M ₁₃	0.32	63	2009	0.16	0.13
M ₄	1.31	100	2010	0.33	0.28
M ₁₂	1.18	100	2010	0.26	0.21
M ₁₃	0.32	93	2009	0.22	0.18

DAS: Days after sowing; M₄: manure stored for 4 months at 1.31% total N; M₁₂: Manure stored for twelve months at 1.18% total N and M₁₃: Manure stored for thirteen months at 0.32% total N.

date. The slopes for DM of the fitted linear regressions were 0.31, 0.22 and 0.50 for the three manure sources, M₄, M₁₂ and M₁₃, respectively at the first sampling date (63 to 70 DAS) (Table 7). By the second sampling date (93 to 100 DAS), modelled values accounted for 63 to 94% with slopes of 1.99, 1.54, and 0.86 for the three manure sources, M₄, M₁₂ and M₁₃, respectively.

The NEV for all sources of manure compared to inorganic N fertilizer was calculated for both DM and N uptake (Table 9). The NEV for DM at the first sampling (63 to 70 DAS) declined with manure storage times from 0.27, 0.19 to 0.16, in M₄, M₁₂ M₁₃, respectively. As the season progressed (70 to 100 DAS), the NEV for DM improved to 0.33, 0.26 and 0.22 in M₄, M₁₂ M₁₃, respectively. The NEV for N uptake was slightly less than DM production for all manures and sampling times though followed a similar trend (Table 9).

DISCUSSION

Nitrogen response curve

The growth of canola showed a positive linear response to increasing rates of inorganic-N fertilizer up to 200 kg N ha^{-1} throughout the growing seasons (Figure 1). The significant increase in N uptake with increasing inorganic-N fertilizer indicated that mineral N was readily taken up by plants ($P < 0.05$; Tables 5 and 6). Concentrations of shoot N were below the critical concentration required for maximum yield (Reuter and Robinson, 1997) for all treatments throughout the experiment. This indicated that N was the limiting factor for plant growth on this infertile site as all other basal nutrients were provided. The low rainfall may have reduced potential yield over both years during the experiment, though still enabled the NEV in the manure to be calculated relative to inorganic-N.

Mineralisation of organic nitrogen in cattle manure

The application of inorganic-N resulted in higher yields compared to all sources of stockpiled cattle manure-

N (M₄, M₁₂ and M₁₃) at equivalent rates of application ($P < 0.001$). Cattle manure typically comprises over 97% of total N in the organic fraction, which is slowly mineralized to inorganic N before it is available to plants (Larney and Angers, 2012). The design of the experiment accounted for the high solubility of inorganic-N fertilizer (urea) which was applied as a split application over the growing season to prevent N loss, whereas cattle manure was applied as a single application. The supply of N from the stockpiled manure treatments compared to inorganic N fertilizer showed that cattle manure was not adequate to supply the N requirements for plant production in the short term owing to the low rate of mineralization where soil fertility was low.

Nitrogen equivalent values (NEV) of cattle manure compared to inorganic fertilizer

At all N rates and sampling dates, the percentage NEV of the three cattle manure treatments compared to inorganic N fertilizer ranged from between 16 and 33% for DM production and between 11 and 28% for N uptake, with lower values noted as the storage time of the manure increased (Table 9). Other researchers have shown a wide variation in NEV up to 59% for cattle manure in comparison to inorganic-N fertilizer in the first year of application due to factors such as the quality of the manure (the species, age and production level of the animal and diet), housing, manure collection and manure storage systems; further influenced by crop type and soil properties (Table 1). For example, manure applied as slurry or to irrigated crops may have a higher NEV, for example, values of 40 to 70% reported by Zhang et al. (1998) in the first year of application to irrigated corn. In cattle on better diets, the value can be higher also, for example NEV from 40 to 73% reported by Rigby (2008). The low N content of manures used in our study and low NEV reasonably reflects the poor quality diets of cattle in SSA and poor storage conditions of the manure compared to studies elsewhere. Duan et al. (2016) suggest that animal manure when managed and utilized appropriately can replace 70% of nitrogen (N)

demand met through inorganic fertilizers in agriculture. It has long been established that the mineralization of N is generally greater for fresh cattle manure compared with manure stored for longer (Paul and Beauchamp, 1994).

Changes in nitrogen equivalent values (NEV) over the growing season

The release of available N from organic compounds during manure decomposition is very gradual and, in a manure-based cropping system, mineralization continues until after harvest (Mallory et al., 2010; Sousa et al., 2016). Much of this is determined by factors such as organic composition of the residue, soil temperature and water content, drying and rewetting events, and soil characteristics. In our study, the NEV of cattle manure increased over the growing season from 15 to 21% for each measure of crop response. The results indicate that on average approximately five times more total N equivalent would be required in manure to obtain comparative plant growth where all other nutrients are not limiting. The NEV of manure compared to inorganic-N may increase further past the 100 DAS used in this study. It has been shown that longer-term accumulated applications of cattle manure release a sufficient supply of N each year to meet crop nutrient requirements without the annual addition of inorganic fertilizers (DeLuca and DeLuca, 1997; Helgason et al., 2007).

For each sampling date, NEV for manure compared to inorganic N was higher for DM production than for N uptake over both sampling times (Table 9). This would tend to indicate that factors in the manure other than N, such as other nutrients, organic matter and soil chemistry contributed to plant growth. For example, a neutral soil pH preferred by plants is often maintained by cattle manure (Benke et al., 2008). Although soil pH and other parameters were not tested in this study, they may have influenced plant growth. As this study was conducted in a dryland temperate environment, the N mineralization rates may differ from tropical conditions where soil properties, soil moisture and temperatures may be different and needs to be confirmed.

Effect of storage on nitrogen content in manure

In this study, increasing the storage time of cattle manure reduced its ability to supply N to the plant. The concentration of total N in manure ranged from 1.31% at 4 months (M_4) storage to 0.32% at 13 months (M_{13}) storage. In comparison, fresh cattle manure typically has a higher N content, for example 2.1% (Pettygrove et al., 2009) and up to 6.2% total N in unstabilized livestock waste in the UK (Rigby, 2008). The concentration of N in manure used in our study was lower than the range of manures used elsewhere, but indicative of cattle manures in SSA.

In our study, cattle manure stored for 4 months (M_4) had a mean NEV of 30% for DM production and 19% for N uptake compared to inorganic N over two sampling dates. As the storage time of the manure increased to 13 months (M_{13}), the mean NEV reduced to 19% for DM production and 15.5% for N uptake compared to inorganic N over two sampling dates (Table 9). Gale et al. (2006) and Heinrich (2009) found that manure and other organic materials could be grouped into categories with similar N mineralization rates based on how they were produced, treated, and stored. This parameter is a very important determinant of the fertilizer value or nutrient use efficiency of the manure after its field application (Rashid et al., 2013, 2017a; Shah et al., 2016, 2018). Generally, stockpiling is not that effective in maintaining N in manure; for example, Shah et al. (2016) found that N recovery by maize for various treatments was as follows; fermented manure (39% of the field applied N) followed by the manure end products obtained from storing it in roofed building (31%), stockpiled (29%) or turned during storage (20%). In stockpiled manure, losses of ammonium will occur reducing the total N content and rainfall will further reduce N content due to the leaching of nitrate. Losses of total N occur following handling and transport which release ammonia to the atmosphere with good storage necessary to retain the fertilizer value of manure and improve crop yield (Holmes, 2007; Gooch and Wedel, 2010). High NEV, up to 70% has been reported when manure is stored for shorter periods of time (Powell et al., 2010). The application of freshly excreted manures incorporated immediately into the soil can improve the nutrient value of the soil (Gachimbi et al., 2009). However, some storage time of manure is required as the ammonia in fresh manure can burn crops if applied directly to the crops (Muhereza et al., 2014). The spreading of manure can result in the loss of ammonia (NH_3), especially during warm, dry weather (Stelt et al., 2007).

Rates of cattle manure required to optimize plant growth

Compared to inorganic fertilizers, higher volumes of manure must be applied for equivalent plant growth. For example, in order to supply 100kg N ha, approximately 25 dry t ha of aged (4 months) cattle manure (~1.3% total N) would be required. The large volumes of manure required would be difficult to source and apply and may not be feasible for smallholder farmers. As the total N content of the manure decreases with storage (that is, ~0.32% total N), the higher volumes required are not practical to apply. Application rates of cattle manure could be reduced by improving the quality of manure through better storage to reduce the loss of N. Storage could be improved using covered shelters and impermeable floors to better retain N prior to spreading.

Organic recycling practices such as mulching, composting and manuring are well known in SSA and may help to reduce N loss (Zake et al., 2005; Gichangi et al., 2006; FAO, 2019).

Barker (2010) reported that cattle weighing 454 kg body weight produce 26 kg of faeces of fresh manure per day, with a total annual production including bedding of 16-18 tonnes of manure. An application of 49,421 kg ha⁻¹ of good quality wet manure per year (that is, 5 cattle) would supply about 225 kg of total N. Hence, 49 t wet manure ha⁻¹ is often referred to as the agronomic rate of application, with N application based on the amount required by crops. From this application, about 45 kg N has been suggested as potentially available (Barker, 2010). To put this into perspective, manure from a total of one to two cattle would be required to fertilize a hectare of crop in SSA to provide the N equivalent of 100 kg ha⁻¹. However, the body weight of cattle in SSA is smaller than the Barker (2010) study due to lower quality diets including limited pastures and no supplementary feeds and compounded by lack of improved breeds. Hence in SSA, the use of cattle manure as a fertilizer is constrained by low manure output and quality.

Other options to improve crop N nutrition

Other options to improve crop N nutrition in SSA should be explored and could include supplementation of cattle manure with inorganic-N fertilizer. Nyamangara et al. (2005) concluded that smallholder farmers in Zimbabwe and similar SSA countries could exploit the combined application of manure and N fertilizer to increase maize yield. Opportunities exist to incorporate more effective crop rotations with legume crops to make better use of N₂ fixation by rhizobia and beneficial microorganisms and could reduce the amount of synthetic N fertilizer needed to maintain the N balance. The release of N bound in crop residues contributes to overall N fertility (Danga et al., 2009; Tonitto and Ricker-Gilbert, 2016). In addition to an overall increase in soil N by legumes, the benefits to healthy farming systems from crop rotations have been well established (St. Luce et al., 2016; Grant et al., 2016; Bainard et al., 2017). Benefits include effective weed control, breaking the persistence of soil-borne pathogens, increasing crop tolerance to abiotic stress, improved soil properties and improved soil microbial biodiversity. Overall, a diverse rotation system will enhance the long-term resilience of the farm system (Abraham et al., 2014; Thiessen et al., 2015). In order to improve adoption of a legume rotation systems approach at the local farm level, relevant economic and agro-environmental policies are required in SSA.

Conclusion

The N equivalent value of cattle manure compared to

inorganic-N fertilizer was dependent on its N content and hence analysis of the N content in cattle manure prior to use is essential for calculating agronomic application rates. The storage of cattle manure from 4 months to 13 months decreased the total N content from 1.3 to 0.32% and reduced N available for plant growth; therefore, better storage conditions of cattle manure are needed to reduce N loss over time. The N equivalent value of cattle manure stored for 4 months (1.3% total N content) was approximately 30% for DM production and 19% for N uptake over the growing period compared to inorganic-N fertilizer and reduced significantly when stored for up to 13 months. The volumes of cattle manure required to satisfy the N fertilizer recommendations compared to inorganic fertilizer may be impractical and further options need to be explored, such as supplementation with inorganic fertilizer or the inclusion of crop rotations with legume crops.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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