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Effects of storage methods on chemical composition of manure and manure decomposition in soil in small-scale Kenyan systems

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ABSTRACT

As a soil amendment, cattle manure enhances soil mineral N content if managed correctly. Manure management varies among smallholder Kenyan farms, yet the quality of manure produced by different methods has not been assessed. This study examined the effects of storage method on the manure N composition and degradability in the soil. Nitrogen composition of manure from cattle fed high and low quality diets, stored under different containment, shading, and manure addition methods was monitored for 30 days. Manure aged 30 days was buried in soil in large- and small mesh litterbags. The disappearance of organic N was monitored over 112 days. Time in storage ($P < 0.03$) and farm of origin ($P < 0.0001$) were the only variables to influence manure organic N content. Origin ($P < 0.04$) and time in storage ($P < 0.0001$) were also the only variables that affected manure mineral N content. Manure N derived from cows fed a higher quality food (Medium quality manure) disappeared faster than manure N derived from cows fed a lower quality food (Low quality manure). More N may be available for uptake by plants during one growing season if manure from better-fed cattle is used as a soil amendment.

1. Introduction

Livestock manure, when used as a soil amendment, is an important tool for improving soil fertility on smallholder farms in Africa. Manure application to soil is a means of retaining nutrients on farms and the use of manure can reduce expenses for commercial fertilizers (Lupwayi et al., 2000; Harris, 2002). Nutrient losses from small Kenyan farms often greatly exceed nutrient inputs (Van den Boscha et al., 1998). Proper management and application of manure may slow nutrient depletion on these farms.

In Kenya, manure management varies among smallholders. A survey of farms in Eastern Province, Kenya showed inconsistencies between farms in the containment and shading of the manure, as well as in how often the manure was turned, in what exogenous organic materials were added to the manure, and in how long the manure was allowed to remain in storage (Lekasi et al., 2003). The effectiveness of different storage strategies in producing a soil amendment that contributes to soil fertility in terms of organic matter and mineral nutrients such as NH_4^+ is not well established. For example, the effects of storage structure, the effects of shading of the storage structure, and the nutrient losses occurring during extended periods of storage have not been quantified for smallholder tropical farming systems. Major nutrient losses from manure, especially N losses, have been observed during storage and transport before the manure is applied to the soil (Murwira et al., 1995; Van den Boscha et al., 1998).

The objective of this study was to examine the compositional changes in cattle manure induced by manure storage method, with an emphasis on nitrogenous compounds. It was hypothesized that pits produce manure with more NH_4-N and less refractory N than piles because the exposed surface area of manure in pits is less than that of manure in piles, resulting in a smaller area from which ammonia may volatilize. Another hypothesis was that shaded storage units produce manure with more NH_4-N and less refractory N than units exposed to full sunlight because manure exposed to sunlight is warmer than shaded manure. Ammonia volatilization increases with warmer temperatures. A third hypothesis stated that units to which fresh manure is added daily produce manure with more NH_4-N and less refractory N than units with manure of a single age. Fresh manure contains more readily degradable N and C compounds than older stockpiled manure and fresh manure degrades more quickly in soil than older manure (Atallah et al., 1995). The fourth hypothesis was that large N losses from stored manure occur within the first month of storage. Losses of 12.5% of the initial manure N content were observed in beef cattle manure stockpiled for 42 days (Luebbe et al., 2008). The fifth hypothesis

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stated that when manure is applied to the soil, manure NH_4-N disappears in the first 2 weeks. Ammonium-N in manured soil fell to trace levels only 1–2 weeks after application (Atallah et al., 1995; Calderón et al., 2004). The disappearance of NH_4-N results from immobilization of the NH_4-N except in manures with a C:N of 8.5 or less (Atallah et al., 1995). In these soils, NH_4 is nitrified and is then susceptible to plant uptake or to denitrification. Denitrification may account for some of the NH_4-N disappearance, since it results in the loss of approximately 5% of manure N after soil application (Calderón et al., 2004). Ammonium-N in the soil solution may be nitrified and become available to plants if the manure application is synchronized with plant nutrient uptake. Nitrification in manured soil produced a net increase in soil nitrate levels during 6 weeks of incubation (Calderón et al., 2004). Finally, it was hypothesized that refractory manure N compounds persist beyond 3 months in soil. An 80-day incubation of manure resulted in C and N mineralization rates that slowed towards the end of the incubation as the pool of readily degradable compounds was depleted by soil microbes, leaving the more slowly degradable cellulose and lignin in the soil (Atallah et al., 1995).

2. Materials and methods

2.1. Manure storage experiment

The manure storage method experiment was conducted during July and August of 2004. A small pasture in Maseno in western Kenya served as the experimental site. Cattle manure from two different research farms in western Kenya was used in the experiment to observe the effects of animal diet on manure quality and the utility of manure as a soil amendment.

The larger dairy farm had a herd of 300 Holstein-Friesian cattle with a milking herd of 90 cows. The cows grazed Rhodes grass (*Chloris gayana*) pasture for half of the day. For the remainder of the day, the herd was confined and fed a balanced ration of corn silage, Napier grass (*Pennisetum purpureum*), and a protein, fat, carbohydrate, and mineral concentrate mix. Manure from the larger farm will be referred to as “Medium quality” manure from this point.

The smaller dairy herd consisted of approximately 75 cattle with 23 animals in the milking herd. The Ayrshire breed dominated the smaller herd, which also included a small number of Ayrshire × Guernsey and Guernsey × Jersey animals. The cows’ diet consisted of ‘cut and carry’ Napier grass and dairy meal that was supplemented with pasture grass consumed while grazing. The amounts of Napier grass, dairy meal concentrate, and pasture grass were fed in no fixed ratio. The pastures consisted of Naivasha Star grass (*Cynodon plectostachyus*), Kikuyu grass (*Pennisetum clandestinum*), and unidentified local grasses.

The inexact diet formulation meant that cows were unlikely to consume the same amount of concentrate from day to day. On the whole, cows in the smaller herd were fed less energy concentrate per cow than the cows of the larger dairy herd. Manure from the smaller dairy herd will hereafter be referred to as “Low quality” manure.

Manure from the milking herds of each farm was collected from the building where the cattle were confined before milking. The differences in cattle diet resulted in differences in the initial composition of the manure used in the study. The Medium quality manure had a smaller total organic N content than the Low quality manure, but the Low quality manure had a larger neutral detergent insoluble nitrogen (NDIN) fraction (Table 1). This implies that the Low quality manure had more N bound in slowly degradable compounds than the Medium quality manure.

Two experiments with randomized complete block designs with repeated measures were conducted (Table 2). One experiment tested the effects of pit or pile containment, manure quality, and frequency of application, while the other experiment tested the effects of containment method on shaded manure. The effects of shade on manure in storage were compared between the shaded units in this second experiment and unshaded units with the same containment and manure quality in the first experiment. In both experiments, 3 replicates of each treatment were incubated in each plot. “Medium quality” and “Low quality” manure units received manure from the larger and smaller dairy herds, respectively. Manure units denoted “One-time” received a single application of 30 kg fresh weight of manure at the beginning of the experiment. In the “Daily” addition treatment, 1.3 kg of manure (fresh weight) were added daily over 30 days. The manure “Pits” were holes with dimensions of 0.76 m × 0.76 m × 0.46 m. Manure was added to the center of the pits. In the “Pile” manure units, manure was added to the center of unbroken ground of each plot. The effects of pit or pile, manure quality, and frequency of application were tested in one randomized experiment.

Treatments for the shading experiment were randomly assigned in a separate randomized experiment. “Shaded” treatments received 50% shade from greenhouse shading material suspended above the manure. “Unshaded” were not shaded with any material (Table 2).

Samples were taken from 5 locations on each pile or pit and mixed together to form composite samples at the start of the incubation and at 6-day interval for the duration of the incubation. After sampling, 10 g subsamples of the manure were immediately stored at 4 °C. These subsamples were extracted in 0.5 N KCl for 30 min using an orbital shaker set at 180 rpm. The extracts were filtered through Whatman No. 42 filter paper (Whatman PLC, Maidstone, Kent, UK). Some particulate matter remained in the samples after filtering, so the samples were centrifuged for 180 min at 6 × 130 × *g* to remove the particulate matter. The filtrates were stored at 4 °C prior to analysis for NH_4 and NO_3 content. The NH_4-N content was measured using the colorimetric method of Anderson and Ingram (1993). Nitrate-N was analyzed by colorimetric reaction using salicylic acid (Anderson and Ingram, 1993). These procedures were conducted in the soil analysis laboratories of the World Agroforestry Centre station in Maseno, Kenya and of the World Agroforestry Centre Headquarters in Nairobi, Kenya.

Table 1
Initial composition of manure used in the storage experiment.

Ingredient	Manure source	
	Low quality	Medium quality
Total N (% of OM)	3.5	3.1
NDIN (% of OM)	1.8	1.4
ADIN (% of OM)	1.2	1.1

Table 2
Treatments in the manure storage experiments testing the effects of manure quality (medium quality vs. low quality), frequency of application (daily vs. one-time), exposure to sunlight (unshaded vs. shaded) and containment method (piles vs. pits).

Containment method	Shading	Application method	Manure quality
Pile	Unshaded	One-time	Low quality
Pit	Unshaded	One-time	Low quality
Pile	Unshaded	One-time	Medium quality
Pit	Unshaded	One-time	Medium quality
Pile	Unshaded	Daily	Low quality
Pit	Unshaded	Daily	Low quality
Pile	Unshaded	Daily	Medium quality
Pit	Unshaded	Daily	Medium quality
Pile	Shaded	One-time	Low quality
Pit	Shaded	One-time	Low quality
Pile	Shaded	Daily	Low quality
Pit	Shaded	Daily	Low quality

The remainder of each manure sample was dried at ≤60 °C and ground to pass a 0.5 mm screen using a Foss Tecator UDY Cyclone mill (Foss, Hillerød, Denmark). The samples were also analyzed for total N using the Kjeldahl method (AOAC, 2000) and for neutral detergent insoluble N, NDIN, and acid detergent insoluble N, ADIN (Licitra et al., 1996).

2.2. Litterbag experiment

On the final day of the storage incubation, 40 g samples (DM basis) from each manure pile and pit of the manure storage experiment were collected and placed in litterbags. This occurred 12 days after the end of the storage experiment for the shaded treatments and on the final day of the storage experiment for all other treatments. The start of the litterbag experiment for the shaded treatments and the other treatments were staggered by 12 days to allow the litterbags to be cleaned and reused. For each pit and pile, 14 litterbags of each of the two mesh sizes, large and small mesh, were prepared. Litterbags were constructed from stainless steel wire mesh (Buffalo Wire Works, Buffalo, NY, USA and Johnson Screens, St. Catherine's, Ontario, Canada). Stainless steel mesh was used instead of a more flexible material such as nylon to prevent destruction of the bags in soil by termites and ants. The square litterbags were 20 cm on a side. Large mesh litterbags were constructed with 8-mesh screen with square apertures of 6.05 mm^2. These large pore litterbags were used to observe the interaction of soil mesofuna and microarthropods with decomposing organic matter *in situ* (Kaneko and Salamanca, 1999). The largest soil insects and animals, members of the soil "macrofauna", are unable to pass through the apertures of the large mesh (Sands, 1998). Small mesh litterbags were constructed using 50-mesh screen with an aperture of 77,841 μm^2, which restricted access to the manure by soil macro- and mesofauna. This mesh size prevents the creation of microenvironments within the manure with altered evaporation and decomposition processes that might have existed if a smaller mesh size (<50 μm) had been used (Vossbrinck et al., 1979; Bradford et al., 2002). The use of two mesh sizes allowed for the differentiation of the degradation activities of the microorganisms from those of the larger soil fauna.

The litterbags were buried in furrows at a depth of 15 cm in a field at the Maseno site which had been uncultivated for more than 10 years, and had received no applications of inorganic fertilizer and minimal organic fertilization from grazing animals during that period. Two large mesh litterbags and two small mesh litterbags containing manure from each pit/pile were removed from the soil after 4, 8, 12, 24, 48, 78, and 112 days of incubation between August and December of 2004. The contents of the litterbags were weighed immediately after being unearthed. Individual 5 g subsamples from each litterbag sample were stored at −20 °C. The remainder of each sample was dried at <60 °C and ground with a Foss Tecator UDY Cyclone mill to pass a 0.5 mm screen.

The frozen subsamples were thawed and assayed for NH_4-N at the soil analysis laboratory of the World Agroforestry Centre headquarters in Nairobi, Kenya using the Chaney-Marbach colorimetric NH_4 assay (Chaney and Marbach, 1962). The dried manure samples were analyzed for total N by the Kjeldahl method (AOAC, 2000) and for NDIN and ADIN (Licitra et al., 1996).

2.3. Statistical analysis

The manure storage experiments were designed as multi-factor mixed models with four fixed factors and one random factor. The fixed factors were application type, pit or pile, days in storage, and manure quality (for the first experiment) and shading (for the second experiment). The individual manure unit was the blocking factor. All possible interactions between the fixed effects were tested. The model was computed using the PROC MIXED procedure of the SAS software (SAS Institute Inc. v 9.1).

The litterbag experiment was designed as a multi-factor mixed model with five fixed factors and one random factor. The fixed factors were application type, pit or pile, days in soil, litterbag mesh size, and manure quality/shading. The random factor was the individual manure unit from which the manure originated. All possible interactions between the fixed effects were tested. The model was computed using the PROC MIXED procedure of the SAS software (SAS Institute Inc. v 9.1). Comparisons were made using the Student's *t*-test.

The effect of the individual manure unit on the results was assessed by calculating the difference between the restricted log-likelihood of the model with individual manure unit included as a random variable and the restricted log-likelihood of the model excluding the individual manure unit. The statistical significance of the difference was assessed using the χ^2-test of independence ($\alpha = 0.05$). This assessment was conducted for the manure storage experiment model and for the litterbag experiment model.

Using the PROC NLIN procedure of the SAS software (SAS Institute Inc. v 9.1), exponential decay models were developed to describe the OM, total N, NDIN, and ADIN dynamics of manure in storage and the OM dynamics of manure in litterbags. Decay models with one exponential term were fitted to the data using the equation $Y = \alpha\, e^{kx}$, where Y represents the OM, total N, NDIN, or ADIN content of the manure, x represents the number of days the manure was incubated in storage or in soil, and k represents the rate of decay of the OM, total N, NDIN, or ADIN in the manure. Regression of the data using double exponential decay equations failed to converge.

3. Results

Mineral N is represented by NH_4-N in this study. Cattle feces contain essentially no urea (Muck and Richards, 1983; Bussink and Oenema, 1998). Manure nitrate levels were analyzed and found to be below the detection limit.

3.1. Manure storage experiment

Results of the mixed model analyses appear in Tables 3 and 4. Neither the application method (daily, one-time), the containment method (pit, pile), nor the presence of shade affected the manure NH_4-N, organic N, and fiber-bound N content at any time ($\alpha = 0.01$). The individual manure unit had a significant effect on the DM, total organic N, ADIN, and NDIN content of the manure in the manure quality experiment. The individual manure unit accounted for 4.3% of the variation in total organic N, 41.7% of the variation in ADIN, and 16.0% of the variation in NDIN. The NH_4-N data were not affected by the individual manure unit. The individual manure unit had no effect on the variance of any of the results in the shading experiment.

The NH_4-N concentrations in manure from both sources increased during the first 6 days in storage, from 689 to 795 mg NH_4-N per kg of manure (DM basis) in the Low quality manure and from 428 to 519 mg NH_4-N per kg of manure (DM basis) in the Medium quality manure. That the Low quality manure contained more NH_4-N at the start of the experiment than the Medium quality manure was unexpected. But NH_4-N losses were greater from the Low quality manure during 30 days of storage. By the end of 30 days of storage, manure NH_4-N fell in the Low quality manure to 414 mg NH_4-N per kg of manure (DM basis) and in the Medium quality manure to 419 mg NH_4-N per kg of manure (Fig. 1). At the end of the 30-day experiment, the Medium quality manure contained 98%

Table 3
ANOVA results for NH_4-N content (mg NH_4-N/kg manure, DM basis), dry matter content (DM, % of fresh mass), organic matter content (OM, % of DM), N content (N, % of OM), acid-detergent insoluble N (ADIN, % of OM), and neutral-detergent insoluble N (NDIN, % of OM) of manure in storage.

Effect[a]	*P*-value						
	DF[b]	NH_4-N (mg/kg manure DM)	DM (%)	OM (% of DM)	N (% of OM)	ADIN (% of OM)	NDIN (% of OM)
Medium quality vs. Low quality manure [A]	1	0.0393	<0.0001	<0.0001	0.5707	0.6447	0.0013
One-time application vs. daily application [B]	1	0.151	0.1684	0.6552	0.1278	0.3396	0.005
Manure pit vs. pile [C]	1	0.6601	0.3737	0.5681	0.1515	0.2101	0.9462
Days in storage [D]	5	<0.0001	<0.0001	0.3681	<0.0001	<0.0001	<0.0001

[a] Fixed effects are the manure quality (medium quality vs. low quality), the manure application rate (one-time vs. daily application), the containment method (pit vs. pile), and the number of days the manure spent in storage (0, 6, 12, 18, 24, or 30 days). Interactions between fixed effects were examined, but only interactions that included the days in storage were significant at $\alpha = 0.05$, so the full results were not included.
[b] DF represents the degrees of freedom of the test.

Table 4
ANOVA results for NH_4-N content (mg NH_4-N/kg manure, DM basis), dry matter content (DM, % of fresh mass), organic matter content (OM, % of DM), N content (N, % of OM), acid-detergent insoluble N (ADIN, % of OM), and neutral-detergent insoluble N (NDIN, % of OM) of manure in storage.

Effect[a]	*P*-value						
	DF[b]	NH_4-N (mg/kg manure DM)	DM (%)	OM (% of DM)	N (% of OM)	ADIN (% of OM)	NDIN (% of OM)
Manure pit vs. pile [A]	1	0.272	0.4504	0.5169	0.9605	0.7491	0.6773
Days in storage [B]	5	<0.0001	0.2328	0.7993	<0.0001	0.0005	0.0784
Shade vs. no shade [C]	1	0.41	0.2808	0.1207	0.5075	0.3146	0.9307

[a] Fixed effects are the presence or absence of shade, the containment method (pit vs. pile), and the number of days the manure spent in storage (0, 6, 12, 18, 24, or 30 days). Interactions between fixed effects were examined, but only interactions that included the days in storage were significant at $\alpha = 0.05$, so the full results were not included.
[b] DF represents the degrees of freedom of the test.

of its initial NH_4-N while the Low quality manure retained only 60% of its initial NH_4-N content.

The Medium quality manure had a smaller OM content than the Low quality manure at the beginning and end of the 30-day storage period (Fig. 2). The Low quality manure contained 67.9% OM (DM basis) at the start of the experiment and 64.3% OM (DM basis) after 30 days of storage. The OM content of the Medium quality manure was 55.9% (DM basis) at the start of the experiment and 50.8% (DM basis) at the end of the 30-day storage period. Single-term exponential regression models of the OM dynamics appear in Fig. 2. Double exponential regression of OM dynamics of manure in storage failed to converge.

The Low quality manure had greater initial concentrations of total organic N and NDIN than the Medium quality manure ($P < 0.01$, $P < 0.0008$). The Low quality manure contained 3.5% organic N (OM basis) and 1.8% NDIN (OM basis) at the start of the storage experiment while the Medium quality manure contained 3.1% organic N (OM basis) and 1.4% NDIN (OM basis) at the start of the storage experiment. The pool of the most refractory fiber-bound N, ADIN, was not significantly larger in the Low quality manure at the start of the experiment ($\alpha = 0.05$). The average ADIN content of manure from both treatments was 1.2% (OM basis) at the start of the exper-

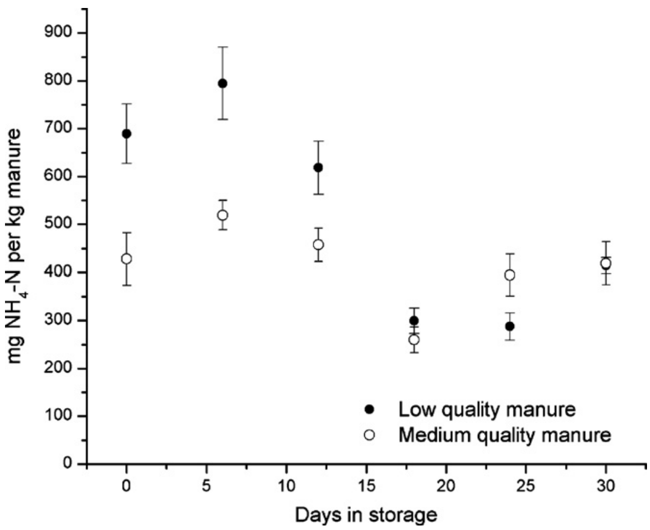

Fig. 1. Ammonium-N dynamics in Medium quality manure and Low quality manure in storage. Error bars represent standard error of means. Discrete points represent the mean values of NH_4-N (mg per kg of manure DM) at each time point.

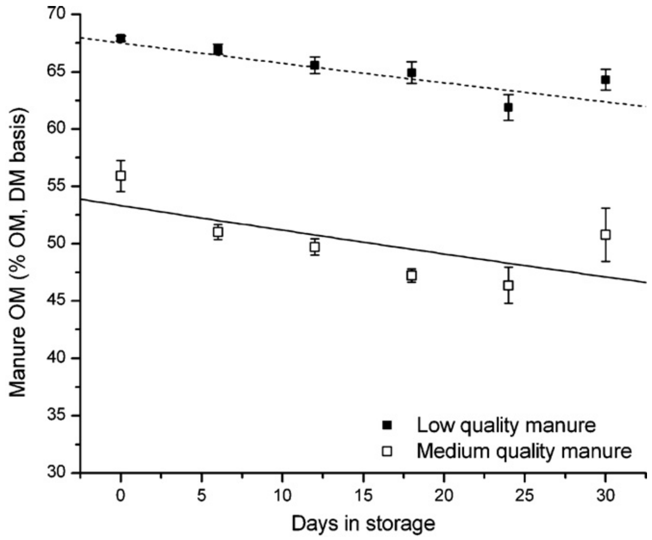

Fig. 2. Total organic matter dynamics in manure in storage (%OM, DM basis). Error bars represent standard error of differences in means. Discrete points represent the mean values of %OM at each time point. Continuous lines represent the best fit regression equations for OM disappearance. *Y* represents the percentage of OM remaining in the litterbag sample. *X* represents the number of days in soil. The solid line (—) represents the best-fit regression line for Medium quality manure treatments. The dashed line (- - -) represents the best-fit regression line for Low quality manure treatments. Medium quality manure: $Y = 53.3358\,e^{-0.00414x}$, $R^2 = 0.990$. Low quality manure: $Y = 67.509\,e^{-0.00264x}$, $R^2 = 0.997$. The rate constants for OM dynamics between the manure sources did not differ at significance level $\alpha = 0.05$.

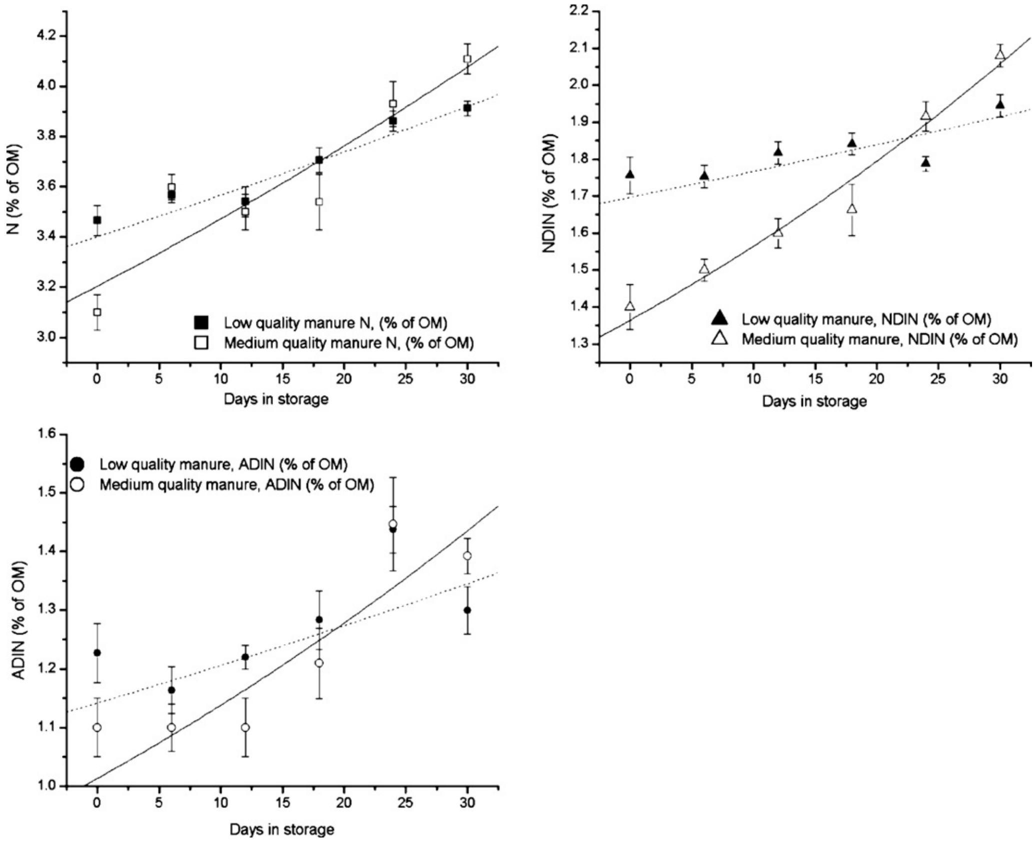

Fig. 3. Total organic N, neutral detergent insoluble N (NDIN), and acid detergent insoluble N (ADIN) dynamics in manure in storage (OM basis). Error bars represent standard error of means. Continuous lines represent regression equations for organic N dynamics in manure during the dry season experiment. Solid lines (—) represent the best fit regression lines for Medium quality manure treatments. Dashed lines (- - -) represent the best fit regression lines for Low quality manure treatments. *Y* represents the amount of organic N, NDIN, or ADIN remaining in the manure (% of initial content, OM basis). (a) Top left: Total organic N dynamics (%N, OM basis). Medium quality manure: $Y = 3.2044\,e^{0.00804x}$, $R^2 = 0.994$. Low quality manure: $Y = 3.4021\,e^{0.00473x}$, $R^2 = 0.997$. The rate constants for organic N dynamics between the two manure sources differed ($P < 0.004$). (b) Top right: Neutral detergent insoluble N dynamics (%NDIN, OM basis). Medium quality manure: $Y = 1.3645e^{0.0137x}$, $R^2 = 0.991$. Low quality manure: $Y = 1.6971e^{0.00403x}$, $R^2 = 0.993$. The rate constants for organic N dynamics between the two manure sources differed ($P < 0.0001$). (c) Bottom left: Acid detergent insoluble N dynamics (%ADIN, OM basis). Medium quality manure: $Y = 1.0135e^{0.0116x}$, $R^2 = 0.977$. Low quality manure: $Y = 1.1419e^{0.00546x}$, $R^2 = 0.980$. The rate constants for ADIN dynamics between the manure sources differed ($P < 0.02$).

iment. Manure ADIN content did differ between the treatments at the end of 30 days of storage ($P < 0.03$). The Medium quality manure contained 1.3% ADIN (OM basis) and the Low quality manure contained 1.4% ADIN (OM basis) after 30 days in storage. At the end of 30 days of storage, the Medium quality manure contained more NDIN than the Low quality manure (2.1% vs. 1.9% NDIN (OM basis), $P < 0.01$). There was no difference in organic N between the two treatments after 30 days of storage. The average organic N content of the manure of both treatments after 30 days of storage was 4.0% (OM basis). Exponential regression models of total N, NDIN, and ADIN dynamics with one exponential term appear in Fig. 3a–c. Double exponential regression models to describe total N, NDIN, and ADIN dynamics of manure in storage failed to converge.

3.2. *Litterbag experiment*

Results of the mixed model analyses of the litterbag manure N composition data appear in Tables 5 and 6.

Considerably more organic matter was lost from the large mesh litterbags than from the small mesh litterbags over 112 days in soil ($P < 0.0001$), beginning from 8 days in soil ($P < 0.05$). From the large mesh litterbags, Medium quality manure lost 78.0% of OM and Low

Table 5
ANOVA results for dry matter content (DM, % of fresh weight), organic matter content (OM, % of DM), N content (N, % of OM), acid-detergent insoluble N (ADIN, % of OM), and neutral-detergent insoluble N (NDIN, % of OM) of manure in litterbags buried in soil.

Effect[a]	*P*-value					
	DF[b]	DM (%)	OM (% of DM)	N (% of OM)	ADIN (% of OM)	NDIN (% of OM)
Medium quality vs. Low quality manure [A]	1	<0.0001	<0.0001	<0.0001	0.0822	<0.0001
One-time application vs. daily application [B]	1	0.9566	0.4488	0.4776	0.4712	0.0122
Manure pit vs. pile [C]	1	0.054	0.4474	0.5564	0.0592	0.4394
Days in soil [D]	7	<0.0001	<0.0001	0.0471	<0.0001	<0.0001
Small mesh vs. large mesh litterbag [E]	1	<0.0001	<0.0001	<0.0001	<0.0001	0.0023

[a] Fixed effects are manure quality (medium quality vs. low quality), the manure storage application rate (one-time vs. daily application), the storage containment method (pit vs. pile), the mesh size of the litterbag (small mesh vs. large mesh), and the number of days the manure spent in soil (0, 6, 12, 18, 24, 30, 48, 78, or 112 days). Interactions between fixed effects were examined, but only interactions that included the days in soil were significant at $\alpha = 0.05$, so the full results were not included.
[b] DF represents the degrees of freedom of the test.

Table 6
ANOVA results for dry matter content (DM, % of fresh weight), organic matter content (OM, % of DM), N content (N, % of OM), acid-detergent insoluble N (ADIN, % of OM), and neutral-detergent insoluble N (NDIN, % of OM) of manure in litterbags buried in soil.

Effect[a]	*P*-value					
	DF[b]	DM (%)	OM (% of DM)	N (% of OM)	ADIN (% of OM)	NDIN (% of OM)
Manure pit vs. pile [A]	1	0.6679	0.9472	0.2005	0.2791	0.3789
Days in soil [B]	7	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Small mesh vs. large mesh litterbag [C]	1	<0.0001	<0.0001	<0.0001	<0.0001	0.0047
Shade vs. no shade [D]	1	0.0822	0.1891	0.1057	0.4142	0.9097

[a] Fixed effects are the presence or absence of shade, the containment method (pit vs. pile), the mesh size of the litterbag (small mesh vs. large mesh), and the number of days the manure spent in soil (0, 6, 12, 18, 24, 30, 48, 78, or 112 days). Interactions between fixed effects were examined, but only interactions that included the days in soil were significant at $\alpha = 0.05$, so the full results were not included.
[b] DF represents the degrees of freedom of the test.

quality manure lost 73.4% of OM after 112 days in soil (DM basis). From Medium quality manure in small mesh litterbags 24.3% of OM was lost after 112 days in soil (DM basis). From Low quality manure in small mesh litterbags, 31.1% of OM was lost (DM basis). Exponential decay equations for OM disappearance appear in Fig. 4. Double exponential decay models of OM dynamics of manure in litterbags failed to converge.

The Low quality manure had lower concentrations of total organic N and fiber-bound N than the Medium quality manure at the start of the litterbag experiment: 3.9% organic N and 1.9% NDIN (OM basis) vs. 4.1% organic N and 2.1% NDIN (OM basis), respectively. After 112 days in soil, the Medium quality manure in small mesh litterbags contained 4.4% organic N, 2.3% NDIN, and 1.9% ADIN (OM basis). Medium quality manure in large mesh litterbags contained 3.1% organic N, 1.2% NDIN, and 0.9% ADIN (OM basis). After the 112-day period in soil, the Low quality manure in small mesh litterbags contained 4.5% organic N, 2.4% NDIN, and 2.2% ADIN (OM basis). In large mesh litterbags, the Low quality manure contained 3.1% organic N, 1.3% NDIN, and 0.9% ADIN (OM basis). The quality of the manure ($P < 0.0001$ for total organic N and NDIN) and the litterbag mesh size ($P < 0.0001$) were the only treatments to have a significant effect on total organic N, NDIN, or ADIN. The manure source had no effect on ADIN ($\alpha = 0.05$). The number of days in storage was also significant to the manure composition ($P < 0.0001$ for ADIN and NDIN, $P < 0.05$ for total organic N).

The NH_4-N content of all manure treatments dropped below 1 mg/kg NH_4-N after 4 days in the soil. Such small amounts of NH_4-N were below the detection limit and analyses beyond 4 days were not warranted.

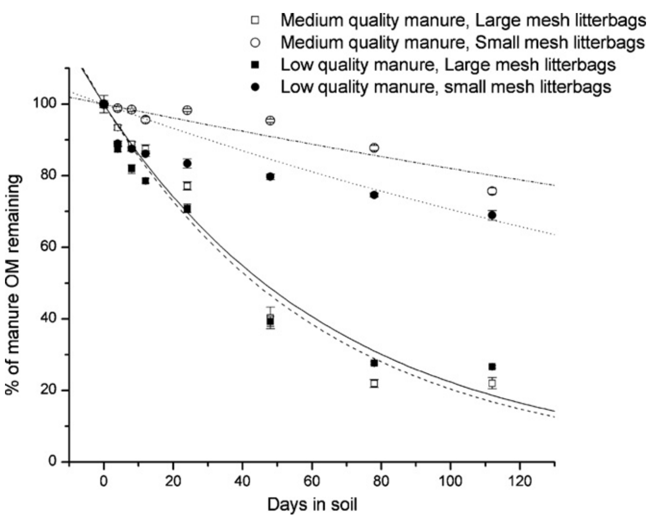

Fig. 4. Fraction of Medium quality manure OM and Low quality manure OM remaining in litterbags buried in soil at each collection day (% of initial OM, DM basis). Error bars represent standard error of differences in means. Discrete points represent the mean values of %OM remaining at each time point. Continuous lines represent the best fit regression equations for OM disappearance. *Y* represents the percentage of OM remaining in the litterbag sample. The dashed line (- - -) represents the Low quality manure treatment in the large mesh litterbags. The solid line (—) represents the Medium quality manure treatment in the large mesh litterbags. The dotted line (- - -) represents the Low quality manure treatment in the small mesh litterbags. The dot-dash line (-·-·-) represents the Medium quality manure treatment in the small mesh litterbags. Solid lines represent Medium quality manure treatments. Medium quality manure, large mesh litterbags: $Y = 100\,e^{-0.0150x}$, $R^2 = 0.989$. Medium quality manure, small mesh litterbags: $Y = 100\,e^{-0.00349x}$, $R^2 = 0.994$. Low quality manure, large mesh litterbags: $Y = 100\,e^{-0.0159x}$, $R^2 = 0.980$. Low quality manure, small mesh litterbags: $Y = 100\,e^{-0.00198x}$, $R^2 = 0.998$.

4. Discussion

4.1. Mineral N of manure in storage

Mineralization of the N in rapidly degradable organic fractions in manure may account for the increase in NH_4-N content seen during the first 6 days of storage: an increase of 15% in the manure NH_4-N content (DM basis) in Low quality manure and an increase of 21% in the NH_4-N content (DM basis) of the Medium quality manure (Fig. 1). The NH_4-N concentration fell during the next 12 days as the N mineralization rate slowed because the pools of labile N compounds in the manure were depleted during the first 6 days. The NH_4-N losses via leaching, volatilization, and incorporation into microbial biomass also contributed to the decrease in NH_4-N concentration. Overall, the data support the hypothesis that manure in storage loses large amounts of N, in the form of NH_4-N, when stored for 30 days. The application rate, the containment method, nor the shading had an effect on any component of manure N composition, so the hypotheses that a daily application rate, manure pits, and shaded systems produce manure with a larger NH_4-N than that of manure of a single age, manure piles, and manure exposed to full sunlight, are not supported. It was hypothesized that shading would reduce NH_3 volatilization from the manure by keeping the manure temperature lower than unshaded manure. The shading material used provided no shelter from rain. Leaching losses of mineral N may have obscured any affect on NH_3 retention contributed by the shading.

4.2. Organic N of manure in storage

The concentrations of organic N, NDIN, and ADIN in the manure increased between 8% and 50% during the last 18 days in storage (Fig. 2). These observed increases in N fractions may be due to a loss of manure mass (Martins and Dewes, 1992). Decomposing material loses mass over time due to the mineralization of nutrients, and other degradation processes that cause structural disintegration (Dresbøll et al., 2006), especially of phenolics and lignin monomers that can be degraded within the 30 days of storage (Bidlack et al., 1992). If the bulk mass of the manure decreases more rapidly than the rate of loss of NH_4-N, the NH_4-N concentration will increase. The failure to develop a two-term double exponential regression equation (Fig. 2) suggests that the decay of both the more degradable organic compounds and the more refractory cellulose and lignin compounds do not greatly differ so as to require two exponential decay terms. The manure in this study came from cows fed low quality tropical forages. Poor quality forage diets lead to manure with more refractory cellulose and lignin compounds than rapidly degradable compounds (Vigil et al., 2002). The fraction of OM capable of being degraded during 30 days of storage may have been too small to warrant its own term.

4.3. Degradation of manure in soil

The hypothesis that manure NH_4-N disappears within 2 weeks of being interred was supported by the data. The NH_4-N content of the manure fell to negligible levels after 4 days in soil. The hypothesis that refractory organic N compounds would remain in soil for more than 3 months without being degraded was supported by the relatively unchanged NDIN and ADIN levels in the litterbag manure over 112 days in soil.

Where there are large soil mesofaunal populations present, a significant portion of manure applied as a soil amendment may be degraded and/or displaced by the soil insects (Seastedt, 1984; Kaneko and Salamanca, 1999; Esse et al., 2001). This is relevant for many areas in western Kenya with large indigenous populations of termites and ants in the soil. Termites have gut cellulases used to degrade the fibrous manure material. Termites and ants use the fibrous manure material in their mounds, so the activity of these insects may result in the relocation of manure from the soil as they transport it to their mounds (Potts and Hewitt, 1973; Diamond, 1998). When manure in litterbags was buried in the topsoil, the manure in the large mesh litterbags lost OM to a greater extent and more rapidly than that in the small mesh bags because of the activity of the soil mesofauna (Fig. 4). Similar effects have been observed in other studies of African agroecosystems (Esse et al., 2001). These losses did not occur in the small mesh litterbags because the mesofauna could not pass through the smaller apertures. In addition, the large mesh apertures allowed for more contact between the manure and the soil. The larger apertures allowed for more manure degradation to occur since more sites are accessible for degradation (Seastedt, 1984). Exponential regression was successful when only one term was used, suggesting that the fraction of refractory cellulose and lignin compounds in manure, originating from the poor quality forages in the cattle diets, was large. The pool of degradable compounds may have been too small for its degradation in soil to be described by a separate term in the exponential regression.

4.4. Impact of diet on manure composition

The Medium quality manure came from cows fed a superior diet compared to the diets of the cows producing the Low quality manure. The Medium quality manure retained more NH_4-N during storage which was then available to the soil upon application. At the end of the litterbag experiment, more of the refractory fiber-bound N remained in the Low quality manure. This N was not mineralized during 4 months in soil. These observations suggest that the quality of manure and its contribution to soil mineral N and to overall soil fertility depend on the diet of the cattle that produce the manure. Cows fed higher quality diets (lower in lignin and indigestible fiber, higher in digestible energy and protein) produced feces with more labile N compounds than more poorly-fed cows that consume diets with less digestible energy and protein and more lignin and indigestible fiber. The feces, when placed in storage, may produce manure that contributes more to the soil mineral N pool and to soil fertility during a single season. This direct relationship between diet quality and manure quality has been observed previously under similar conditions: feeding concentrates has resulted in elevated levels of manure N and organic C (Lekasi et al., 2001).

The manure OM and organic N that remained in soil for the full 112 days are likely very refractory since they were not degraded after 4 months. The data suggest that the fibrous portions of manure persist beyond a single growing season. These fibrous materials may contribute to overall soil fertility by increasing the soil organic matter (SOM), thereby improving soil structure and other physical properties (Havlin et al., 2005). Their contribution to the mineral N pool, however, would be small. In order to ensure that the manure amendment adds to the soil mineral N pool manure with a high mineral N content should be used.

5. Conclusion

The observation that the Low quality manure mineral N content fell significantly after 30 days of storage suggests that manure should not be stored for more than 30 days. Should the manure remain in storage longer, it is possible that there will be very little mineral N or labile organic N present when the manure is applied to the soil. Manure could be stored for only a short time before it is added to soil to maximize the amount of mineral N that may be taken up by plants. Two major drawbacks of a shorter storage time are an increased workload for the farmer because of more frequent applications of manure to soil and less manure available for application at planting time. The farmer must decide if a larger mineral N content in manure justifies the extra labor.

The results of this study suggest that further scrutiny of manure storage methods practiced on small farms in Kenya is needed to determine their effects on manure N composition. The treatments tested in this study, emulating storage methods in use on the small farms, had no effect on the final manure quality. However, manures from only two sources were tested and the manure was not amended with cattle urine, feed refusals, or bedding, all of which may alter the decomposition patterns of manure in storage and in soil. Environmental effects on manure quality, such as effect of rainfall on N losses from manure in storage, should also be addressed in future experiments so that a more complete picture of the N dynamics of manure in storage on smallholder Kenyan farms.

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