Plant Soil (2010) 328:253–269
DOI 10.1007/s11104-009-0107-x

REGULAR ARTICLE

Carbon and nutrient losses during manure storage under traditional and improved practices in smallholder crop-livestock systems—evidence from Kenya

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Received: 4 December 2008 / Accepted: 8 July 2009 / Published online: 31 July 2009

Abstract In the absence of mineral fertiliser, animal manure may be the only nutrient resource available to smallholder farmers in Africa, and manure is often the main input of C to the soil when crop residues are removed from the fields. Assessments of C and nutrient balances and cycling within agroecosystems or of greenhouse gas emissions often assume average C and nutrient mass fractions in manure, disregarding the impact that manure storage may have on C and nutrient losses from the system. To quantify such losses, in order to refine our models of C and nutrient cycling in smallholder (crop-livestock) farming systems, an experiment was conducted reproducing farmers' practices: heaps vs. pits of a mix of cattle manure and maize stover (2:3 v/v) stored in the open air during 6 months. Heaps stored under a simple roof were also evaluated as an affordable improvement of the storage conditions. The results were used to derive empirical models and graphs for the estimation of C and nutrient losses. Heaps and pits were turned every month, weighed, and sampled to determine organic matter, total and mineral N, P and K mass fractions. Soils beneath heaps/pits were sampled to measure mineral N to a depth of 1 m, and leaching tube tests in the laboratory were used to estimate P leaching from manure. After 6 months, ca. 70% remained of the initial dry mass of manure stored in pits, but only half of or less of the manure stored in heaps. The stored manure lost 45% of its C in the open air and 69% under roof. The efficiencies of nutrient retention during storage varied between 24–38% for total N, 34–38% for P and 18–34% for K, with the heaps under a roof having greater efficiencies of retention of N and K. Laboratory tests indicated that up to 25% of the P contained in fresh manure could be lost by leaching. Results suggest that reducing the period of storage by, for example, more frequent application and incorporation of manure into the soil may have a larger impact on retaining C and nutrient within the farm system than improving storage conditions.

Keywords Sub-Saharan Africa · Carbon dioxide emissions · Green house gases · Nutrient balances · Integrated soil fertility management · Low-technology composting · Leaching · Volatilisation

Responsible Editor: Elizabeth M. Baggs.

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Abbreviations

HOA manure heaps stored in the open air
POA manure pits stored in the open air
HUR manure heaps stored under a roof

Introduction

In the absence of mineral fertilisers or other nutrient inputs, animal manure may be the only nutrient resource available to African farmers to fertilise their crops, and often is the only input of C to the soil where crop residues are removed from the fields after harvest. Nutrients may be brought into the farm system by livestock grazing in communal land, through feedstuffs bought or collected to feed them, or in mineral fertilisers. In the first two cases nutrients are cycled through animal manure. In the third, manure may play an important role in improving nutrient recovery efficiencies and yield response by crops when applied in combination with mineral fertilisers (e.g. Bationo et al. 2006), or where mineral fertilisers are applied to soils with a past history of manure use (Vanlauwe et al. 2006; Zingore et al. 2007; Tittonell et al. 2008a). Gaseous losses during manure handling and storage not only represent a net loss of C and nutrients from the farm system, but also impact on the overall greenhouse gas balance at farm scale through the emission of CO_2, CH_4 and N_2O (Steinfeld and Wassenaar 2007). Several management factors influence manure decomposition and nutrient losses, some of which can be controlled by introducing small changes into the management of manure during collection and storage.

Of all the factors that may influence C and nutrient cycling within the farming system, the efficiency of retention of these elements during manure collection and storage is most critical (Rufino et al. 2006). Yet, whilst changes in nutrient concentrations are commonly reported, few studies report mass losses during manure collection and storage, and this prevents the analysis of the efficiency of nutrient cycling at farm or farming system scale. In smallholder farming systems of East and southern Africa the most common systems of manure storage include heaps or piles, pits, or manure left in the kraals and collected just before planting (e.g., Nzuma and Murwira 2000; Lekasi et al. 2002). Manure stored in heaps or pits is normally mixed with other organic materials such as crop residues, tree prunings or litter, kitchen ashes, etc. The practice of actively and deliberately composting manure is less frequent, and often the collected excreta are thrown in a pit together with household wastes. In fewer cases farmers keep the heaps under a simple roof, or covered with materials such as straw or plastic film, as observed among some smallholder dairy farmers in the highlands of Kenya (Onduru et al. 2008). Urine is rarely collected with manure in these systems, except where dairy cattle are stalled in hard-floored 'zero grazing' units.

Manure is stored for variable periods of time, but normally in between planting times. In regions where two cropping seasons per year are feasible, such as in the Kenya highlands, manure is stored for about 6 months. The quality of manure after storage has an impact on nutrient release and crop response when applied to the soil, and on the long term dynamics of soil organic matter (e.g., Okalebo et al. 2006). Different storage systems produce manures of varying quality in terms of nutrient content, including cases in which up to 90% of the mass in the collected manure is sand (Mugwira and Murwira 1997). Mass losses from manure stored in heaps reported for African smallholder systems ranged from 15% to 50%, depending on the conditions and duration of storage (Lekasi et al. 2002). Isolated studies including controlled experiments, modelling and on-farm measurements, suggest that N losses during storage may account for 30–50% of all N losses from manure (Rufino et al. 2007). Losses of phosphorus (P) by leaching from stored manure have seldom been reported for Africa (e.g., Brouwer and Powell 1998), but have been measured more often in manure-amended soils in temperate regions (e.g., Brock et al. 2007).

In spite of such variability, C and nutrients dynamics during manure storage in tropical farming systems are often disregarded and average, fixed technical coefficients (in the form of mass fractions or loss factors) are used to estimate e.g. CO_2-C or NH_3-N emissions from stored manure (e.g., Herrero et al. 2008). Simulation models used to calculate nutrient balances and cycling within farming systems, and in particular their 'manure modules', must be calibrated against measurements of changes in the total content (and not only their mass fractions) of C and nutrients during storage (e.g., Chivenge et al.

2004; Rufino et al. 2007). Datasets of this type are often lacking for African smallholder systems, and especially those that comprise different storage methods replicating farmers' practices.

An experiment was conducted in western Kenya with the objective of quantifying C and nutrient losses from manure stored under traditional smallholder practices (manure stored in heaps and in pits) that create different storage environments in terms of moisture, aeration and temperature regimes. The magnitude of the losses of C and nutrients through different processes (gaseous losses or leaching) were estimated. To refine calculations of C and nutrient cycling in smallholder (crop-livestock) farming systems, this study proposes simple models to estimate C and nutrient losses from manure during storage based on experimental measurements.

Materials and methods

Experimental site and set up

The experiment was conducted in the backyard of the tree nursery of the Kenya Forestry Research Institute (KEFRI) at Maseno, western Kenya (0° 1′ 0″ S, 34° 36′ 0″ E; 1503 m.a.s.l.). This location allowed easy access to the experiment to farmers from the surroundings, controlled management and safe handling of sampling and measurements. The storage methods were designed to resemble local practices of manure storage and were conducted during the same period as that in which farmers normally store manure. Western Kenya is characterised by a bimodal rainfall regime that allows two cropping seasons per year (Fig. 1). At the beginning of each rainy season farmers plough their fields and apply the manure that has been stored during the previous season. Crop residues are added to the manure heap/pit as the crop harvest proceeds, and is rarely done all at once. Excreta is also added to the stored manure throughout the storage period. For this experiment, however, it was necessary to premix excreta and crop residues in a representative proportion observed locally (Castellanos-Navarrete 2007). This was done at the beginning of the experiment, and no other material was added during storage. It was assumed that it takes farmers about 2 months of manure collection to accumulate an amount (fresh mass) that represents a heap/pit of typical dimensions (±300 kg). For this reason, the experiment was set up in October 2006 (about 2 months after planting time) and terminated in April 2007 (cf. Fig. 1). The number of treatments and replications in the experiment were limited by the amount of manure of relatively homogeneous quality (from the same origin) that could be gathered.

Material collection

Between 11 and 25 October 2006, cattle excreta were collected at the experimental farm of Maseno University, from a herd of 20 dairy (crossbred Friesian and Ayrshire) cattle in lactation, with an average milk production of 8 L cow^{-1} day^{-1}, and an average body weight of 300 kg. During this period,

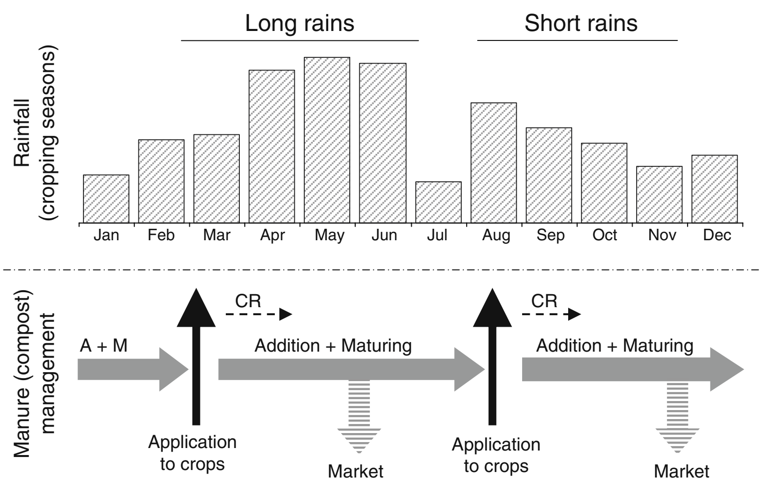

Fig. 1 Schematic representation of an operations calendar for manure management by smallholder farmers in western Kenya, depicting the rainfall pattern on top (double cropping) and the periods during which manure is stored; the *dotted lines* indicate the period shortly after harvest during which crop residues (CR) are added to manure, and the *discontinuous lines* indicate intermittent sale of manure (Market)

cows were fed a daily diet consisting of: 70 kg fresh weight cow^{-1} of Napier grass, 3.5 kg cow^{-1} of dairy meal (dry cows got only 1 kg a day) and c. 1 kg FW cow^{-1} of banana stalks. Molasses were added to the ration at a rate of 7 L in the daily bulk of dairy meal (of 70 kg). Water consumption was 80 L cow^{-1} day^{-1}. Cows were kept on a paddock dominated by unpalatable grass species from 7.30 to 13.00 h and from 16.00 to 18.00 h daily. Fresh excreta were collected mostly from hard floored stalls, containing small fractions of urine, and partly from the yard around the zero grazing units, which may have been contaminated slightly with soil. Only fresh faeces excreted the same day were collected; those exposed to weather for more than 24 h (rained on or sun dried) were not collected. All excreta collected were stored under a roof (with open walls) in an uncovered pile resting on a plastic sheet. The excreta were almost completely free of plant material such as bedding or feed refusals. The total quantity of excreta at the end of the collection period of 14 days was ca. 2.7 t fresh weight (c. 20% DM content). Maize stover was collected from a single field at Maseno University farm. It had been removed from the field after harvest on the last week of August 2006 and piled in the open air for c. 60 days. The total amount of maize stover collected was c. 200 kg air dry weight.

Layout of the experiment

Three treatments were laid out: (i) compost heaps in open air (HOA), (ii) compost pits in open air (POA) and (iii) compost heaps under roof (HUR), with three experimental units per treatment (Fig. 2). While the dimensions and environmental conditions of the HOA and POA treatments reproduced the conditions under which farmers store manure, the HUR was tested as an affordable improvement of storage conditions. The HUR were located under a 2.3 m-high roof made of semi-transparent glass fibre sheets inclined for drainage, and open walls. The HOA and POA treatments were located in an adjacent field (about 15 m away from the HUR site) that was fenced. The experimental units were placed contiguously without randomisation, due to the impossibility of randomising the treatment under roof. All treatments, both under roof and open air were shaded by nearby trees and buildings during early morning and late afternoon. To avoid run-on of rain water towards the experimental units, 30 cm-deep ditches were dug across the slope, upslope along the width of the experiment. To avoid contamination between experimental units due to drainage and/or run-off, heap and pit replicates were placed 1 m away from each other and 20 cm-high ridges were built in between them. A drainage

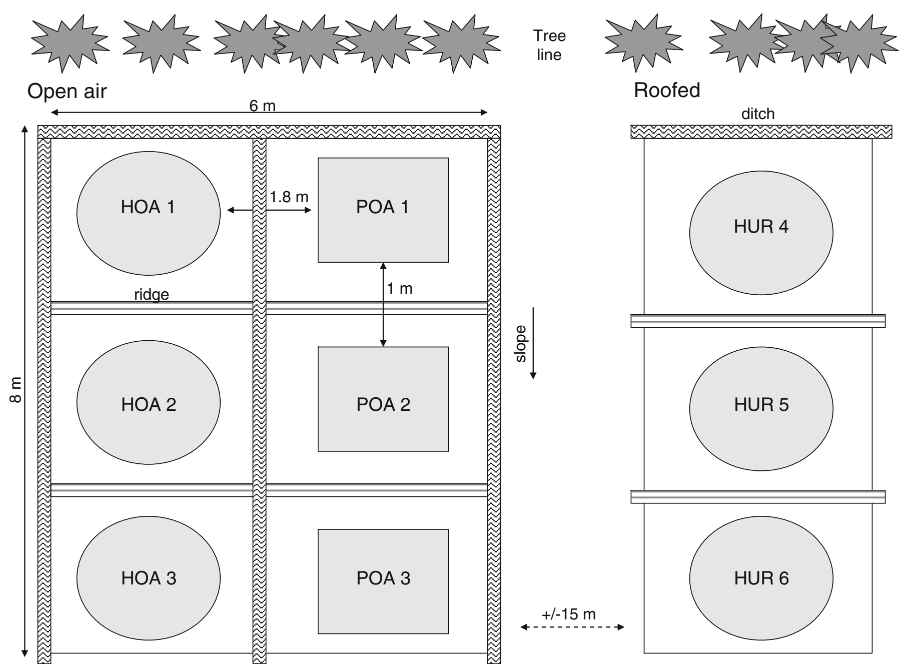

Fig. 2 Map of the experimental setup, described in Section "Layout of the experiment", and showing the distribution of the three observations per treatment: heaps in the open air (HOA), pits in the open air (POA) and heaps under roof (HUR). The terrain had a slope of ca. 1% and was shaded by trees and buildings during the morning and late afternoon

ditch was also dug between the rows of heaps and pits in the open air site. The soil on which the heaps were placed was levelled (terraced) prior to the experiment.

The fresh excreta collected from the dairy farm was mixed thoroughly to homogenize differences in quality that could have been caused by different residence times in the collection pile (ranging from 1 day to 15 days). The excreta were then mixed with maize stover (previously chopped to 20 cm) in a volume ratio 2:3 using wheelbarrow load counts (6:9). The weights (± standard error) of wheelbarrow loads of fresh excreta, dry maize stover and of the manure mixture were determined: fresh excreta, 51.7 ±0.58 kg; dry maize stover (chopped), 2.3 ± 0.12 kg; manure mix 2:3 v/v excreta:stover: 28.3 ± 2.66 kg. Heaps of approximately conical shape of 1.5 m basal diameter and 70 cm height were built with the manure mix, averaging 332±15 FW kg per heap. Pits of 1×1 m and 0.6 m deep were dug and filled with the same amount of the mix of excreta and stover used to build the heaps. Two additional heaps were built as controls, without replications, and placed next to the rest of the heaps: one heap of pure excreta and one heap of pure maize stover. They had the same shape and dimensions as the other heaps and were sampled for laboratory analysis as the rest of the treatments. The results of these analyses were used to cross-check those from the main treatments. The quality and nutrient composition of the materials used in the experiment is given in Table 1.

Management and monitoring

The experiment started on October 28, 2006 and the heaps and pits were turned three times during storage (as practiced locally). On December 7, January 9 and February 8 (40 days, 73 days and 103 days of storage, respectively) all the material was removed from the heaps/pits and weighed, and heaps/pits were re-built by placing the former surface material at the bottom and *vice versa* to simulate the operation of turning the heap/pit. On April 26 all the material from the heaps/pits was removed and weighed. A rain gauge and a max/min thermometer were installed next to the experiment to record daily rainfall and air temperatures. Temperature was measured every morning at 09.00 h and every afternoon at 13.00 h at the centre of the heap/pits throughout the experiment. pH was monitored in the field on 1:2.5 suspensions of samples taken from the heaps twice a week using pH strips.

Sampling and laboratory analysis

Initial sampling

Six samples of excreta of approximately 0.5 kg each were taken from the initial collection pile at the end of the collection period, two close to the upper surface of the pile, two from the centre and two from the bottom. These samples were quickly but thoroughly mixed on a plastic film and three sub-samples of 0.3 kg were packed in polythene bags, sealed and stored at 4°C in a coolbox prior to analysis of mineral N, total N, P and K, water and ash content and pH. Three samples of approximately 0.3 kg each were collected from the centre of the bulk of maize stover (chopped to 20 cm pieces and mixed throughout) and analysed for total N, P, K and water content. After mixing excreta and stover in the selected proportion (2:3 v/v) and prior to the construction of manure pits and heaps, three samples were taken, mixed, and a composite sample of 0.3 kg was sent to the laboratory for analysis of mineral N, total N, P and K, water and ash content and pH. This procedure was repeated three times during the process of heap/pit building (i.e. three composite samples were sent for analysis).

Table 1 Composition of the materials used to establish the manure storage experiment

Material	Dry matter (g kg^{-1})	Organic C (g kg^{-1})	Total N (g kg^{-1})	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	P (g kg^{-1})	K (g kg^{-1})	Ash (g kg^{-1})	pH
Excreta	202	399	18.4	1056	165	6.5	10.4	248	8.0
Maize stover	605	384	4.5	99	52	0.1	3.2	297	8.1
Mix (2:3 v/v)	278	359	14.3	703	79	5.0	10.2	321	8.2

All mass fractions for nutrients and C are expressed on a dry matter basis

Regular sampling

Samples were taken from the heaps/pits every 30 days throughout the experiment, from three points around the centre (about 20 cm from it) on three imaginary axes separated by an angle of 120 degrees, and about 20 cm deep into the heap/pit (one auger-head deep). These samples were mixed to generate a composite sample of each experimental unit (cf. Fig. 2), totalling nine composite samples per sampling date. Samples were taken at 40 days, 73 days, 102 days and 182 days of storage (the original plan was to sample at 30 days, 60 days, 90 days and 180 days of storage, but heavy rains delayed the first sampling by 10 days). Samples for mineral N were taken before the compost was removed for weighing. Samples were sealed in plastic bags, stored at 4°C in a coolbox and sent to the laboratory for analysis of mineral N and water contents and pH the following day. Composite samples (including the surface, centre and bottom positions) were taken from the manure mix at every turning and at the end of the experiment and analysed for mineral N, total N, P and K, ash and water contents. After sub-sampling the remaining material was returned to the heaps/pits.

Soil sampling for mineral N

To assess N losses through leaching from stored manure, soil samples were taken from underneath the heaps/pits and from control soil on the same experimental field. Samples were taken on December 7 (after 40 days storage) at 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm and 80–100 cm depth from the soil beneath the open air heaps (HOA) and at 60–80 cm and 80–100 cm from beneath the pits (POA) and at 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm and 80–100 cm depth from the soil beneath the pure manure and maize stover control heaps. The soil beneath the pits was sampled while the material was being removed for weighing and turning. The soil beneath the heaps under roof (HUR) was only sampled for the upper 0–20 cm layer. Samples were also taken at five different points within the experimental field were the experiment was placed. These samples were bulked per depth, corresponding to 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm and 80–100 cm. Samples were stored at 4ºC and analysed for mineral N (NH_4-N and NO_3-N) the following day.

Laboratory analysis

Samples were oven dried at 55°C and ground to pass through a 1-mm sieve. Organic matter was analysed by loss on ignition (Okalebo et al. 2002). A 10 g sample was taken and ignited at 550°C for 8 h and the ash weighed on a fine balance. To convert the percent organic matter content to total C the loss on ignition was multiplied by the coefficient 0.526 determined by Kirchmann and Witter (1992). While we acknowledge that C contents in organic matter will vary according to its composition and change during composting, within the approximate range of 40 – 60%, this value was seen as more conservative than the 58% often assumed in simple calculations for soil organic matter (Stevenson 1986). N, P and K were analysed after complete oxidation of the materials by a modified Kjeldahl digestion using sulphuric acid (Okalebo et al. 2002). Samples were pre-treated with sodium salicylate to convert NO_3 to NH_4, and hydrogen peroxide was added as oxidising agent. N was determined from 5 mL aliquot of the digestion mixture using an auto-analyser (Sklalar Analytical BV, The Netherlands), K was determined by flame photometry and P colorimetrically using the molybdate-blue method. Mineral N was determined in potassium chloride extracts through a cadmium-reduction method (Dorich and Nelson 1984). The pH was determined on water extracts (1:2.5 manure/water), as described by Anderson and Ingram (1993).

A simple laboratory test was conducted to measure the potential for P leaching from manure during storage. PVC tubes of 10 cm diameter and 20 cm long were filled with 100 g (DW) manure. An iron mesh, filter paper and sterile sand were placed at the bottom of the manure columns. Water was applied daily during 6 days, totalling of 600 mL (equivalent to ca. 75 mm rain in a week). The leachate was collected on days 1, 2, 3 and 6 and analysed for P concentration colorimetrically.

Data analysis

The dry weight of the heaps/pits (kg) at each weighing date was calculated from their fresh weights and dry matter fractions (%). The concentrations of C, N, P and K were used to calculate the total content of these elements per heap/pit, and expressed in kg SU^{-1}, where SU stands for storage unit and corresponds to a pit or a heap containing ca. 100 kg of manure dry matter. The three experimental units of each treatment were considered replicates in ANOVA's performed to test the effects of storage practice (pit open air, heap open air, heap under roof), days of storage (40, 73, 102, 182) and their interaction. Single exponential models of the form: $Y_t = Y_e + (Y_0 - Y_e) \times exp^{-rt}$ were used to describe statistically the changes in manure dry weight and in its total content of C, N, P and K (kg) during the period of measurement. The parameters Y_0 and Y_e (in Y units) represent the initial and final levels of Y_t, respectively, and r is the relative rate of change of the state variable over time (t). The analyses were done using GenStat, 10th release.

The measurement of changes in carbon during manure storage in heaps, in the open air and under roof, were used to fit the C mineralization model of Yang and Janssen (2000), in which the organic matter is treated as a single component. Pits were discarded because the stored manure was contaminated with run-on soil particles, so that changes in C could not be attributed reliably only to decomposition. The model of Yang and Janssen is based on the principle that the logarithm of the average relative mineralization rate (K) of a substrate considered as a whole is linearly related to the logarithm of decomposition time (t, years). The equation is: $K = R\, t^{-S}$, or: $\log K = \log R - S\, \log t$, where R (dimension t^{S-1}) represents K at $t=1$, and S (dimensionless, $1 \geq S \geq 0$) is a measure of the rate at which K decreases over time, also called the speed of `ageing' of the substrate. The quantity of the remaining substrate, Y_t, is calculated by $Y_t = Y_0 \exp(-Rt^{1-S})$, where Y_0 is the initial quantity of the substrate. The actual relative mineralization rate (k) at time t is proportional to K, according to $k = (1-S)K$. This model was tested against an assembly of 136 sets of data collected from trials conducted in 14 countries all over the world, covering periods of months to tens of years and materials of widely different quality (Yang and Janssen 2000).

Both the statistical model fitted against the measurements of organic matter in manure over time and the model of Yang and Janssen (2000) were used to generate graphs to assist in estimating CO_2 emissions from manure stored under different conditions over variable periods of time.

Results

Effect of storage practice on manure quality

The conditions under which manure was stored affected its final quality and nutrient composition (Table 2). After 6 months, about 70% remained of the initial dry mass of manure stored in pits, but only 50% or less of the manure stored in heaps. The manure heaped under a roof had significantly higher mass fractions of dry matter and ash, and less C than the other two treatments. The manure stored in pits in the open air had significantly lower mass fractions of total and mineral N than the manure in both heaps, and slightly lower of P. The mass fraction of K was notably larger in the manure stored under roof, and did not differ significantly between the pit and heap in the open air. Most of the mineral N in the manure stored in pits was NH_4-N, whereas NO_3-N was predominant in the manure stored in heaps. Roofing had a significant impact on the mass fractions of NH_4-N and NO_3-N. When compared with the quality of the manure at the beginning of storage (cf. Table 1), the manure stored in pits had mass fractions of N of 60% less, P of 32% less and K of 75% less after the 6 months of storage. In the manure stored in heaps in the open air the mass fraction of total N declined by 20% and that of K by 67% during storage. The manure stored in heaps under a roof conserved about the same mass fractions of P and total N, and 20% less K, as compared with the beginning of the experiment.

Changes in mass and storage conditions

The rate of mass loss from stored manure was significantly affected by the storage conditions (Fig. 3a). The exponential models fitted to the data points had root mean squared errors (RMSE) of 0.8 kg, 2.1 kg and 1.4 kg for the pits in open air, heaps in open air and heaps under roof, respectively (regression ANOVA $P<0.01$). Most losses of dry matter took place during the first 3 months for the three storage conditions. Manure stored in heaps under a roof, losing close to 50% of its initial dry weight in the first month of storage, decomposed faster than manure stored in the open air. Manure stored in pits in the open air decomposed at the slowest rate, and retained significantly more dry

Table 2 Quality attributes of manure (a mix 2:3 v/v of cattle dung and maize stover) after 182 days of storage under different conditions in western Kenya

Treatment	Dry Wieght (kg) (A)	Mass remaining (%)	Dry matter (g kg^{-1})	Organic carbon (g kg^{-1})	Ash (g kg^{-1})	pH	Total nitrogen (g kg^{-1}) (B)	C to N ratio	Mineral N (mg kg^{-1})	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	Phosphorus (g kg^{-1})	Potassium (g kg^{-1})
Pit open air	69.4	73	534	199	627	7.1	5.7	35	19	16	3.0	3.4	2.6
Heap open air	46.5	53	515	198	627	6.9	11.2	18	290	17	273.0	4.9	3.3
Heap under roof	38.6	46	751	109	793	7.0	14.2	8	491	36	455.0	4.7	8.1
SED	6.8	6	49	15	39	0.3	2.0	3	139	10	141.3	0.8	0.8
Significance	0.010	0.009	0.005	0.008	0.008	ns	0.014	0.001	0.039	ns	0.049	ns	0.010

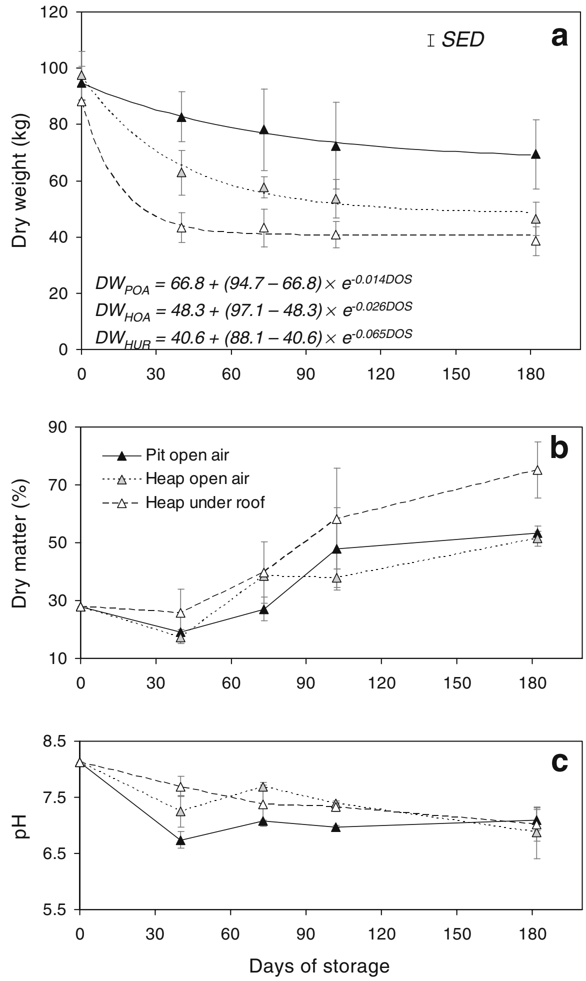

Fig. 3 Changes in total dry mass (**a**), dry matter mass fraction (**b**) and pH (**c**) of a mix of cattle manure and maize stover (2:3 v/v) stored during 6 month under three different practices. In panel A the lines indicate exponential models (*full line* for pit open air; *dotted line* for heap open air; *dashed line* for heap under roof) fitted to the data points (*triangles*). The *grey bars* indicate the standard error of the mean. DW: dry weight; DOS: days of storage; POA: pit in open air; HOA: heaps in open air; HUR heaps under roof; SED: standard error of the differences

matter than the other treatments after 6 months of storage. The heaps in the open air exhibited an intermediate behaviour. At the end of the storage there were no significant differences in the amount of dry matter retained in both heap systems, in open air or under roof, but the heaps under roof had a significantly larger proportion of dry matter (Fig. 3b). The control heap of pure excreta kept in the open air during the experiment decomposed at a comparable rate to that of the heaps under roof (not shown), losing 50% of its dry mass after 3 months, whereas the heap of pure maize stover retained 66% of its dry mass after 6 months of storage. The pH of the manure decreased from an average of 8.1 to 7.0 during storage, without significant differences between storage practices at the end of the storage (Fig. 3c). The manure stored in pits in open air had a significantly lower pH than the heaps after 40 days of storage (pH 6.7 on average) and after 102 days (6.9 on average).

Part of the differences observed in the rate of change in manure mass during the first 2 months of storage may be ascribed to the pattern of rainfall during the season of the experiment. Most of the seasonal rainfall fell at the beginning of the season, with a total of 841 mm in the first 60 days of the experiment (Fig. 4a). This led to wide differences in the temperature of the manure stored in pits and heaps, and in the open air vs. under roof (Fig. 4b; cf. dry matter fraction in Fig. 3b). After the first heavy showers the manure stored in pits in the open air cooled down abruptly to below air temperature and remained within such range during the rest of the storage period. The manure stored in heaps under roof reached a peak of 53°C after 5 days of storage

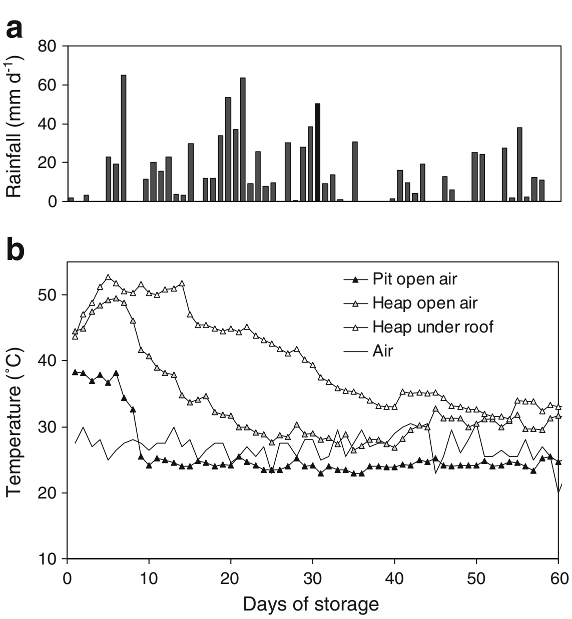

Fig. 4 **a** Daily rainfall and **b** air and compost temperature recorded during the first 60 days of the experiment. A total of 841 mm rainfall was recorded in 60 days. Temperatures were taken at the centre of the pits or heaps; each point represents the average of three replicates

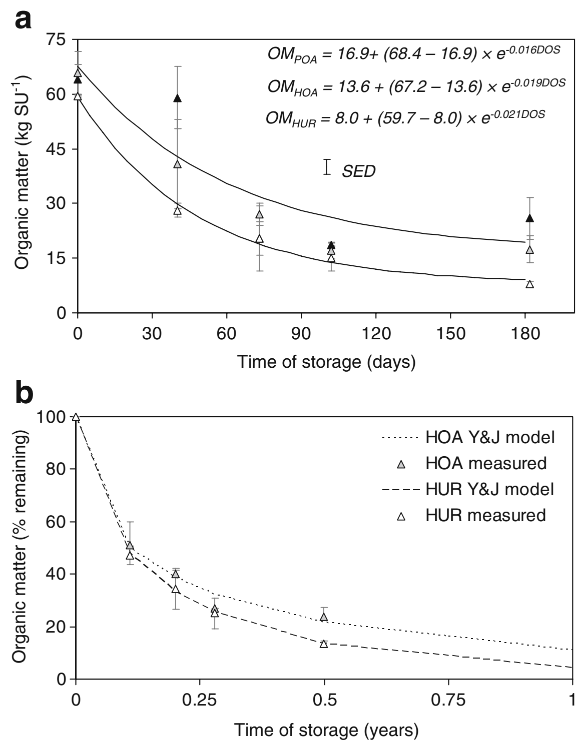

Fig. 5 **a** Measured changes in the total amount of organic matter contained in manure stored during 180 days under three different practices. **b** Measured and modelled percentage of organic matter remaining with respect to its initial amount, using the model of Yang and Janssen presented in Table 4, for the two heap treatments. In panel A, the markers correspond to measurements and the lines to the exponential models fitted (*full line* for pit open air; *dotted line* for heap open air; *dashed line* for heap under roof). *Grey bars* indicate the standard error of the means. DOS: days of storage; POA: pit in open air; HOA: heaps in open air; HUR heaps under roof; SED: standard error of the differences. SU stands for storage unit, corresponding to a pit or a heap of ca. 100 kg DM of manure

indicating thermophilic decomposition, remained above 50°C until day 14, and then decreased converging to air temperature, and stablised at 2°C to 3°C higher than the air until the end of the experiment. The temperature of manure stored in heaps in the open air converged to air temperature after a month of storage and remained slightly lower than the heaps under roof until the end of the experiment.

Carbon losses

The total amount of manure organic matter decreased to about a quarter of its initial amount after 3 months

Table 3 Changes in the mass fraction of carbon (C) and nutrients in manure stored during 6 months under three different management practices. Averages are followed by their standard deviation except for the initial values. SED: standard error of the differences

Days of storage	Mass fraction (g kg^{-1})										C:N	C:P
	C		N		P		K		Min N			
Pit open air												
0	358		14.3		5.0		10.2		0.78		25	72
40	378	±20	16.4	±0.2	5.1	±0.6	1.9	±0.5	0.25	±0.05	23	73
73	157	±98	5.9	±5.6	3.2	±1.4	2.8	±0.5	0.16	±0.03	27	49
102	144	±37	4.9	±1.1	3.2	±1.1	2.8	±0.3	0.23	±0.35	29	45
182	198	±27	5.7	±0.9	3.4	±1.1	2.6	±0.5	0.02	±0.00	35	57
Heap open air												
0	358		14.3		5.0		10.2		0.78		25	72
40	347	±62	18.7	±4.2	6.9	±2.2	4.3	±0.9	0.16	±0.03	19	50
73	249	±12	12.1	±4.4	5.0	±0.8	4.0	±0.0	0.25	±0.05	20	50
102	170	±8	8.8	±2.5	4.1	±0.4	3.6	±0.1	0.07	±0.09	19	41
182	198	±34	11.2	±2.0	4.9	±0.4	3.3	±0.4	0.29	±0.24	18	40
Heap under roof												
0	358		14.3		5.0		10.2		0.78		25	72
40	346	±30	18.5	±3.7	7.1	±0.6	10.7	±0.7	1.16	±0.82	19	49
73	260	±87	15.6	±6.3	6.5	±2.8	9.2	±2.5	1.16	±0.82	17	40
102	194	±40	10.4	±2.4	4.0	±0.6	7.9	±1.0	0.31	±0.25	19	48
182	110	±8	14.2	±3.6	4.7	±1.2	8.1	±1.5	0.49	±0.17	8	23
SED (days of storage)	20		1.5		0.6		0.4		0.16		2.3	4.4
SED (storage practice)	15		1.2		0.4		0.3		0.12		1.8	3.4

of storage (Fig. 5a), partly as a result of changes in the mass fraction of organic matter in the stored manure. This is reflected by the calculated mass fractions of C, which tended to decrease during storage (Table 3). The determination of organic matter mass fractions was subject to relatively large error due to the sampling of a heterogeneous material, which added to the error inherent to the weighing of the fresh manure bulk, particularly for the pits and heaps in the open air after 40 days of storage. Evidence of contamination of manure stored in pits with soil from the surroundings during the heavy rains period was also observed (i.e., variable ash mass fractions). Exponential models fitted to the amount of C in stored manure had RMSE values of 10.1 kg, 2.4 kg and 1.3 kg for the pits in open air, heaps in open air and heaps under roof, respectively ($P<0.01$; Fig. 5a).

The C mineralisation model of Yang and Janssen (2000) was fitted to organic C data from the heaps in open air and under roof, as these were the least contaminated with run-on soil (Fig. 5b). The models predicted the percentage of organic matter remaining in the heaps quite accurately (Table 4), with the rate constant (*K*) decreasing over time, or 'ageing', faster in the open air than under roof (cf. *S* values).

Using these models and an average conversion of organic matter into C of 0.526, the specific CO_2

Table 4 The model of Yang and Janssen (2000) fitted to the heaps treatments of manure storage (cf. Fig. 5b). Time (*t*) is expressed in years

	Heaps in open air	Heaps under roof
Log-linear relationship	$\log K=-0.47 \log t+0.79$ ($r^2=0.91$)	$\log K=-0.34 \log t+1.15$ ($r^2=0.99$)
Parameter values		
R	2.22	3.17
S	0.47	0.34
K (after 0.5 year)	3.09	4.02
Remaining substrate (%)	$Y_t=Y_0\times\exp[-2.22\times t^{(1-0.47)}]$	$Y_t=Y_0\times\exp[-3.17\times t^{(1-0.34)}]$
RMSE (in % units)	2.98	0.63

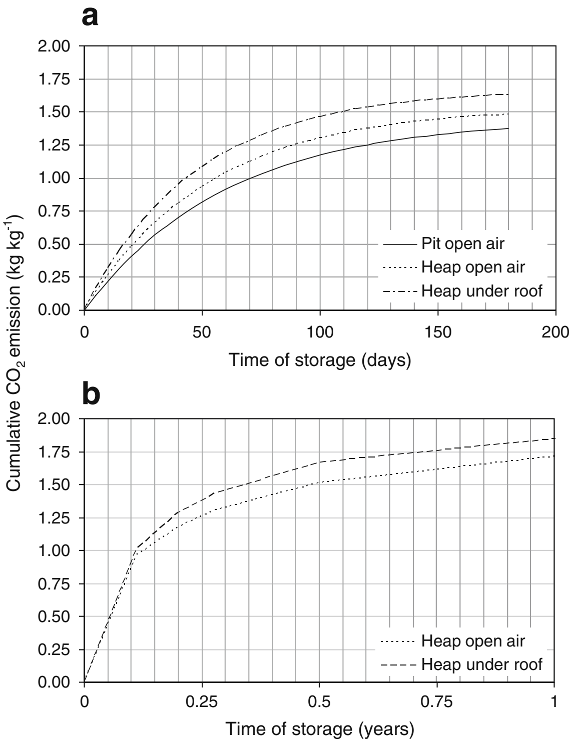

Fig. 6 Graphs to estimate cumulative CO_2 emission coefficients. **c** Apparent cumulative CO_2 emission based on measured changes in manure organic matter for all treatments (cf. Fig. 5a). **d** Cumulative CO_2 emission during 1 year of storage simulated with the model of Yang and Janssen fitted to measured changes in C from the experimental units that were not or least contaminated with run-on soil particles

emission coefficient was calculated for each storage practice, and accumulated over time (Fig. 6a and b). Since the decline in manure C during storage was not only due to C mineralisation, but also to drainage of dissolved organic matter, removal by invertebrates, etc., the use of the statistical models derived from observed organic matter remaining (Fig. 5a) yields 'apparent' CO_2 emission coefficients. The apparent CO_2 release from manure stored in a heap in the open air was c. 1 kg CO_2 per kg of manure (initial weight) after 60 days, c. 1.4 kg after 120 days, etc. (Fig. 6a). The C mineralisation model of Yang and Janssen (2000), that assumes that changes in soil C are due only to decomposition, yielded larger emission values for manure stored in heaps. The extrapolation of storage time up to 1 year using this model indicated a cumulative emission of 1.7 kg per kg manure stored in heaps in the open air. These coefficients may be used for estimating CO_2 emission from stored manure, as often done for the calculation of greenhouse gas balances at farm scale.

Changes in nutrient content and mass fractions

The total amounts of N, P and K contained in the stored manure decreased during storage (Fig. 7) due to a decrease in their mass fraction over time (Table 3). The mass fractions of total N, mineral N, P and K varied significantly between days of storage and between storage practice ($P<0.01$), although for K also the interaction days of storage × storage practice was significant ($P<0.01$). The C:N and C:P ratios of the manure stored in pits in the open air were greater on average than those of the manure stored in heaps, in open air or under roof. As in the case of organic matter (cf. Fig. 5a), the amount of total N calculated for the pit in open air was larger and more variable than for the other storage practices after 40 days of storage (Fig. 7a). The manure stored under roof retained significantly more mineral N and K during storage, particularly during the first 2 months to 3 months of storage (Fig. 7b and d). The parameters of the exponential models and their RMSE are presented in Table 5. According to these models, the efficiencies of nutrient retention during storage (Y_e/Y_0) varied between 24% and 38% for total N, 34% and 38% for P and 18% and 34% for K, with the heaps under roof having greater efficiencies of retention of N and K.

The ratio of mineral to total N (not shown) was greater for the heaps under roof than for the other storage practices throughout the experiment, and larger for heaps than for pits in the open air at the end of the experiment. Most of the mineral N in the manure was in NH_4-N at the beginning of the storage (Fig. 8), and its mass fraction decreased abruptly after 40 days of storage. In the heaps stored under roof mineral N was retained as NO_3-N until 2 months to 3 months of storage, coinciding with the thermophilic decomposition phase (cf. Fig. 4), and losses took place subsequently.

Nutrient leaching

N losses through leaching were assessed by sampling the soil at different depths underneath the pits and heaps in the open air and measuring NH_4-N and

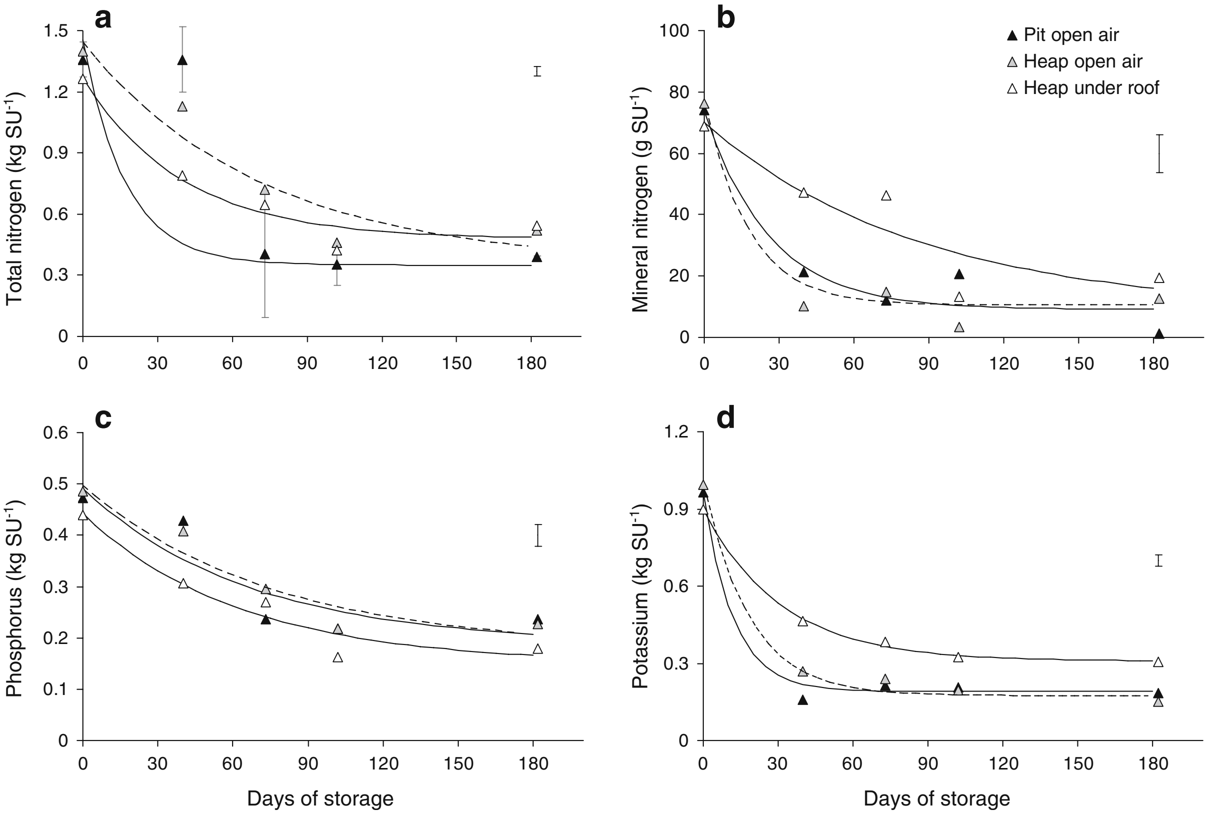

Fig. 7 Changes in the amounts of (**a**) total nitrogen, (**b**) mineral nitrogen, (**c**) phosphorus and (**d**) potassium contained in manure stored during 180 days under three different practices. The markers correspond to measurements and the lines to fitted exponential models (*full line* for pit open air; *dotted line* for heap open air; *dashed line* for heap under roof). *Vertical bars* indicate the standard error of the differences. In panel A, *bars* indicating the standard error of the mean are drawn for the pit open air treatment; the exponential model for this treatment was fitted excluding the measurements at 40 days of storage. The parameters of all exponential models are presented in Table 4. SU stands for storage unit, corresponding to a pit or a heap of ca. 100 kg DM of manure

NO_3-N concentrations in the soil after 40 days of storage (Fig. 9). In the soil underneath the heaps and the pits most of the mineral N measured (c. 80–90%) was in the form of NH_4-N, whereas in the control soil almost half of it was in the form of NO_3-N (volumetric water contents in the soil varied between 18–21%). Mineral N concentrations were greater in the soil underneath the heap of pure excreta kept as control in the open air. The concentrations of mineral N in the first 40 cm immediately under the pits (60–80 cm and 80–100 cm) and the heaps (0–20 cm and 20–40 cm) were similar, with a larger proportion of NH_4-N beneath the pits and of NO_3-N beneath the heaps. Soil samples taken from underneath the control stover pile had similar mineral N values as those of the control soil, and between 50–70% of the N was NO_3-N. Soil samples taken from the 0–20 cm layer beneath the heaps stored under roof had an average mineral N mass fraction as high as 69 mg kg^{-1}, of which about 75% was NO_3-N.

In the additional laboratory test run to assess the potential leaching of P from manure, we found concentrations ranging between 0.12 mg P L^{-1} and 0.29 mg P L^{-1} in manure extracts after leaching an aliquot of fresh manure equivalent to 100 g dry matter with 600 mL of deionized water during 6 days (Fig. 10). This amount of P leached corresponds to 10–24% (19% on average) of the total manure P. This indicates that P can be leached from manure that is too wet or unprotected from rain during storage, leading to a decline in P concentrations in manure over time (cf. Table 3: pits in open air).

Table 5 Parameters of the exponential model ($Y_t = Y_e + (Y_0 - Y_e) \times exp^{-rt}$) fitted to the measurements of changes in nutrient content in 100 kg DM of manure during storage (cf. Fig. 5). Time (t) is expressed in days and r in day^{-1}, Y_0 and Y_e represent the initial and final amounts of nutrients per storage unit

	Y_0	Y_e	r	Y_e/Y_0	RMSE*
Nitrogen (kg SU^{-1})					
Pit open air	1.45	0.35	0.057	0.24	0.24
Heap open air	1.44	0.35	0.014	0.25	0.11
Heap under roof	1.27	0.48	0.025	0.38	0.06
Mineral N (g SU^{-1})					
Pit open air	73.8	9.1	0.038	0.12	5.9
Heap open air	76.3	10.3	0.055	0.14	15.6
Heap under roof	70.0	8.3	0.011	0.12	8.2
Phosphorus (kg SU^{-1})					
Pit open air	0.49	0.19	0.015	0.38	0.05
Heap open air	0.50	0.18	0.013	0.35	0.03
Heap under roof	0.44	0.15	0.016	0.34	0.02
Potassium (kg SU^{-1})					
Pit open air	0.97	0.19	0.080	0.20	0.69
Heap open air	0.99	0.18	0.052	0.18	0.02
Heap under roof	0.90	0.31	0.031	0.34	0.01

SU Storage unit; *RMSE* root mean squared error of the differences

* All regressions were significant at $P<0.01$ except for potassium, at $P<0.001$

Discussion

The different methods of manure storage influenced the final quality and nutrient content of a mix of cattle excreta and maize stover (2:3 v/v) stored during the short rains season in western Kenya. Manure stored in pits or heaps in open air and under roof were subject to different temperature and moisture conditions (Fig. 4) that led to different rates of decomposition (Figs. 3, 5) and nutrient losses (Figs. 7, 8, 9; Tables 2, 3). The differences in mass losses between storage practices were larger during the first 90 days of storage than later on. The efficiency of retention of N, P and K was not larger than 40% under any of the storage practices (cf. Table 5). While N is prone to both gaseous and leaching losses, K and P are lost basically through leaching or through drainage of dissolved organic matter. Evidence of nutrient removal by invertebrates has been reported for manure already applied in the field (Esse et al. 2001). While we observed the presence of larvae and other soil macro organisms in the stored manure, their activity was not formally assessed, as it was not judged to be substantial. After 3 months of storage the differences in nutrient retention efficiencies between storage practices tended to narrow (cf. Fig. 7), indicating that the length of the storage period has a larger influence on C and nutrient retention than the way in which manure is stored.

Changes in organic matter and nutrients in manure during storage were described using exponential models with a lower end term Y_e (cf. Figs. 3, 5, 7 and Table 5). In the case of changes in organic matter over time, however, the suggested 'equilibrium' represented by Y_e would probably not have been reached within the time span of the experiments (i.e., decomposition may continue). In the C mineralisation model of Yang and Janssen (2000) the decomposition of manure is assumed to proceed beyond this time but with a decreasing mineralization rate. To test this

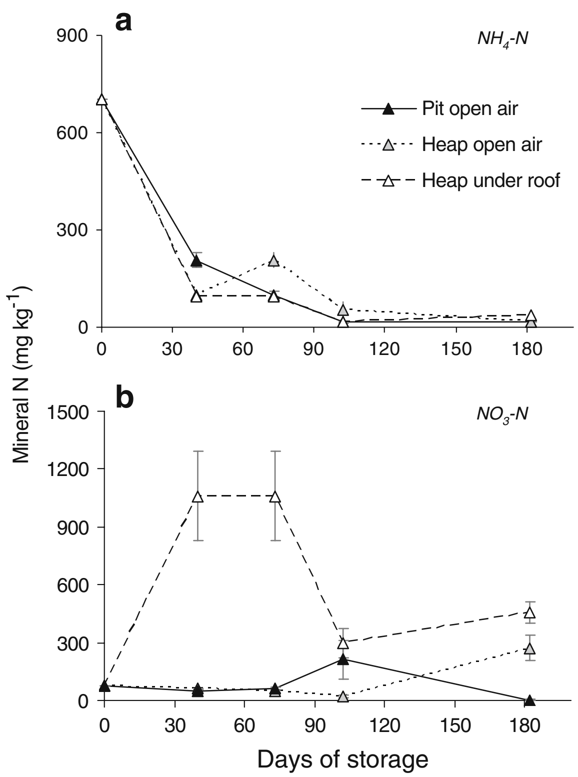

Fig. 8 Changes in the concentrations of **a** NH_4-N and **b** NO_3-N in manure stored during 180 days under three different storage practices. *Grey vertical bars* indicate standard errors of the means

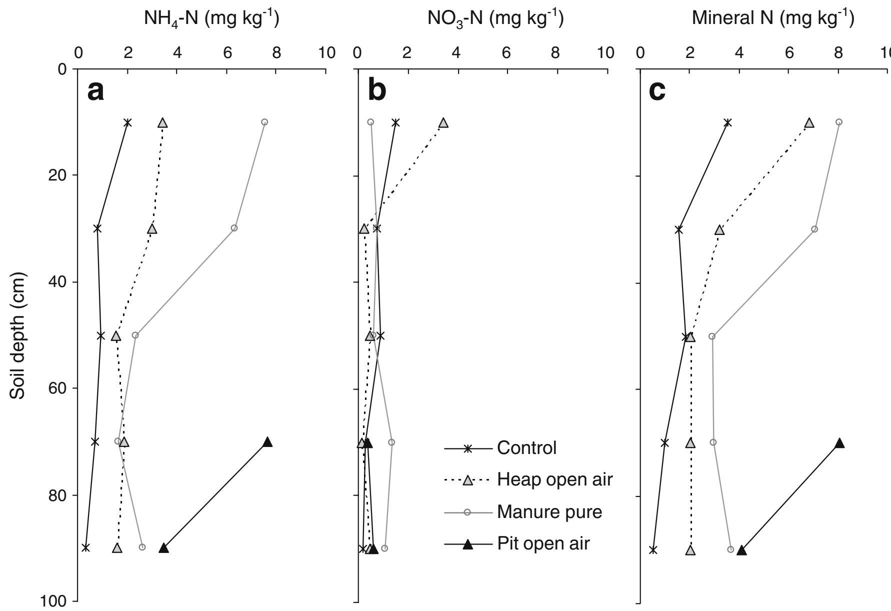

Fig. 9 Mass fractions of **a** NH_4-N, **b** NO_3-N and **c** total mineral N (NH_4-N + NO_3-N) in the soil beneath the heaps and pits in the open air, in a control soil adjacent to the experiment, and in a control heap of manure pure (i.e., without mixing with maize stover) after 40 days of storage

assumption, however, it would have been necessary to adjust the value of C concentration in organic matter at each time, which we kept constant due to lack of measured evidence. Due to this, and to the fact that some of the experimental units (notably the pits in open air) received soil particles through run-on during heavy rains (cf. Fig. 4), the terms of the statistical models fitted to the measurements should be considered as of descriptive rather than of explanatory value.

Losses of N in the order of 60–80% as measured here are similar to those measured in temperate regions from manures with much larger N contents (e.g., Martins and Dewes 1992). Leaching of P from manure has been seldom reported for smallholder systems in Africa (e.g., Brouwer and Powell 1998). The observation that the concentration of P in manure decreased during storage in the open air (cf. Table 3) led us to conduct a simple laboratory test (Fig. 10). Although both inorganic P (orthophosphate) and organic P (organic P-compounds + smaller colloids that may pass through the filter) are leached, only inorganic P was analysed in the leachate collected (cf. Okalebo et al. 2002). This means that our measurements are an underestimate of the actual P leaching through this method. Although some of the colloids could break up in the acid medium of analysis, a correct estimation of leached P requires digestion of the extract. In the field experiment, in addition, a substantial amount of P may have been lost through drainage of dissolved or suspended organic matter during the first 2 months of storage.

Other management practices that were not evaluated here may also contribute to improve nutrient retention during storage. There was more mineral N in the soil beneath the heap of pure excreta compared with the 2:3 v/v mix used in the experiment (Fig. 9), indicating better N retention due to presence of maize stover in the latter. Adding crop residues with a high C:N ratio to manure has been shown to contribute to retaining N, particularly when urine is added to the

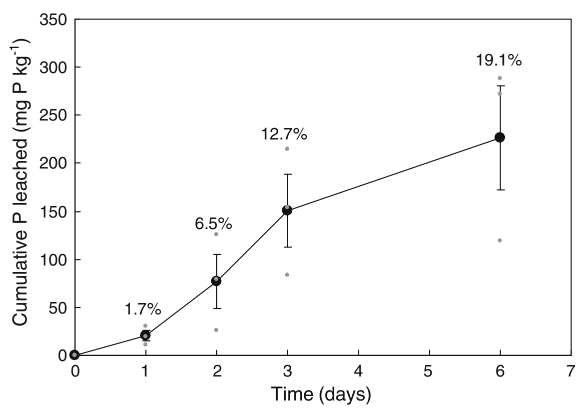

Fig. 10 Cumulative P leached from manure after a week in a laboratory experiment. P was measured in extracts after leaching an aliquot of fresh manure equivalent to 30 g dry matter with 600 mL of deionised water. *Vertical bars* represent the standard error of the mean and *small grey dots* are replicates

manure mix (Lekasi et al. 2003; Nzuma and Murwira 2000). Covering the heaps with a plastic film may also have a positive impact on the efficiency of C and N retention during storage (Rufino et al. 2007). A hard floor may help preventing nutrient losses by leaching, which can be substantial when manure is wet or unprotected from rain (cf. Figs. 9, 10). The initial quality of the manure stored may be also highly variable, as influenced by livestock feeding and management systems, the type of livestock or the type of stalling facilities from where it is collected. The manure used in this experiment had an initial quality that was better than the average manure quality on local farms (Lekasi et al. 2002; Castellanos-Navarrete 2007). Livestock feeding and animal productivity have important consequences for the quality of excreted manure (Delve et al. 2001). Significant linear relationships were observed between the daily N intake and the daily N collected in faeces and urine (Lekasi et al. 2003).

The amounts of C and nutrients that may be cycled on the farm through animal manure are often overestimated. Studies on C flows and balances in African farming systems often assume in their calculations a C mass fraction of 35% in manure, as reported by de Ridder and van Keulen (1990)). This value, however, is only close to what can be observed in manure just excreted, and overestimates the actual C mass fractions of manure that has been decomposed (cf. Tables 2, 3; Fig. 5). Longitudinal surveys show that animal production in a region like western Kenya is mostly limited by feed availability (Waithaka et al. 2002), and the amounts of manure available for crop production at farm scale are consequently small (Onduru et al. 2008). Otieno et al. (1995), however, observed in densely populated areas of western Kenya that two cattle in an intensely managed zero grazing unit produce around one wheelbarrow of manure each day (±25 kg day^{-1}). Based on this, Lekasi et al. (2002) calculated for an average farm of 0.6 ha, an availability of manure for application to crop fields of just over 15 t ha^{-1} yr^{-1}. This is an optimistic estimate. If bedding material and feed refusals are included in the manure mix, it may be assumed that the composition of this manure has similar characteristics to the mix used in our experiment (cf. Table 1). The amount of manure collectable from a zero grazing unit would then represent (365× 0.025=) 9.1 t per year, which we assume to be on a fresh weight basis. This corresponds to 2.5 t of manure dry weight per year and to roughly 1 t C, 36 kg N, 13 kg P and 26 kg K potentially available. According to the results of our experiment, if manure is stored for 5 months to 6 months, less than half of the amounts of C and nutrients mentioned above will be available when manure is applied to the fields (cf. Figs. 5, 7; Tables 3, 5).

The best manure quality in our experiment was obtained with storage in heaps under roof (more favourable C:Nutrient ratios, a drier and less bulky material easier to carry and apply), while the pits in open air retained larger amounts of C but less nutrients. Pits may perform better in drier environments or when manure is stored during a dry season (e.g., Chivenge et al. 2004). However, our results indicate that the length of the storage period has a stronger effect on manure quality and on C and nutrient retention than the storage system. Although a relatively large proportion of carbon and nutrients can be lost from the farm system during manure storage (Figs. 5–10, Table 3), the absolute amounts may not be large when the amounts of manure available on the farm are small. Often crop production cannot be sustained on these amounts of nutrients, and therefore nutrients must be brought in from outside the system. The combined application of small amounts of animal manure with mineral fertilisers improves the utilisation efficiency of the applied nutrients, even when manures are of poor quality (Tittonell et al. 2008b).

Conclusions

Manure handling and storage affect the efficiency of nutrient retention within smallholder crop-livestock systems. In this sense, manure storage may represent either a strategic node of nutrient redistribution or an open gate to nutrient losses from the system, depending on the magnitude of C and nutrient flows through manure. Our results suggest that pit storage of manure could be more suitable for storing manure for long periods with the aim of retaining organic matter in the system, but subject to the trade-off of losing more of the more easily leachable nutrients N and K during storage. Roofing appeared to have a positive effect on manure quality, especially when manure was stored for less than 3 months. Heaps in the open air retained 20% less manure mass than pits but the manure was of better quality. The differences in nutrient retention between storage systems were are not very important after 6 months of storage, but they were during the first 2 months to 3 months. In reality, farmers keep adding fresh excreta to the heaps throughout the storage, so that they store a nutrient richer material, which behaves more closely to what happened during the first months of storage in our experiment. Better utilisation of C and nutrients contained in manure could be obtained by shortening the storage periods by, for example, more frequent application of manure to short-cycle crops such as vegetables, or split applications during the season to annual grain crops. In addition, the effect of the length of the period of storage (i.e., which is different in regions of uni-modal vs. bi-modal rainfall) is sufficiently large that it should be considered within models and calculation procedures to estimate greenhouse gas emissions and nutrient cycling in smallholder crop-livestock systems.

Acknowledgements We thank the European Union for funding this research through the AfricaNUANCES Project (Contract no INCO-CT-2004-003729). We thank Pieter Pijpers and Wilson Ngului and his team for their valuable contribution to this work.

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