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Manure and Soil Fertility Management in Sub-Humid and Semi-Arid Farming Systems of Sub-Saharan Africa: Experiences from Kenya

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Abstract: A study was conducted in the sub-humid Kiambu and in the semi-arid Mbeere districts of Kenya to determine smallholder farmers' manure management practices and quantity and quality of on-farm available manure under different livestock management systems. Data collected from 60 smallholder farmers identified manure management practices to be variable and poor irrespective of management system. The quality of cattle manure in the open grazing systems of Mbeere was poorer (1.22% N; 0.09% P; 2.14% K) and of higher variability than manures from zero-grazing systems of Kiambu (1.41% N; 0.53% P; 1.54% K) where animals are supplied with high quality feed supplements. We calculated the potential manure production to be 3.1 and 0.7 tonnes DM year^{-1} farm^{-1} for Kiambu and Mbeere, respectively. Faced with low manure availability, farmers adopted manure management strategies that included accumulation in livestock pens and or removal from livestock pens and storing over time before spatial and temporal application to selected crops and plots in a rotational pattern. In both study sites, the sole application of manure or inorganic fertilizers proved limited in providing a comprehensive solution to crop nutrient supply. Given this limitation and the differential farmer resource endowments in sub-humid and semi-arid study sites, appropriate strategies for improving manure storage, quantity and quality, efficient manure use and application methods and integrated soil fertility management need to be developed, separately for each livestock management system, to enhance crop nutrient supply.

Key words: Kenya, livestock system, manure, manure quality, semi-arid, soil fertility, sub-humid, tropical farming

INTRODUCTION

In Sub-Saharan Africa (SSA), continual cultivation with inappropriate farming methods has resulted in severe decline in soil nutrients and organic matter posing a serious threat to agricultural production (Smaling, 1993; Bationo *et al*., 1998). This has, partly, contributed to the declining food production over the last three decades in the region (IFPRI, 1996). To increase rural incomes and to meet growing food demands, SSA must improve agricultural productivity by 4% per annum during the next decade (Badiane and Delgado, 1995). Thus, there is an apparent need to identify promising plant nutrient management practices to expand both cash and food crop production, especially, in the phase of rapidly growing population and decreasing per capita land (Keerthisinghe *et al*., 2003).

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Solutions, which have been proposed to reverse nutrient depletion and soil fertility decline, include inorganic fertilizer and organic matter based technologies as well as accompanying measures such as soil and water conservation (Nandwa and Bekunda, 1998). However, fertilizer use in SSA is less than 10 kg ha^{-1} . This contrasts sharply with the more than 50 kg fertilizer ha^{-1}used in Latin America and 80 kg fertilizer ha^{-1} in Asia (Yanggen *et al*., 1998). The use of inorganic fertilizers among smallholder farmers of SSA is constrained by (i) market liberalisation and trade policies that increase fertilizer prices relative to commodity prices; (ii) limited access to markets and inadequate infrastructure; (iii) inefficient functioning of output, input and credit markets; (iv) poverty and cash constraints that limit farmers' ability to purchase fertilizer and other inputs and (v) untimely availability of appropriate types of fertilizers (Pender *et al*., 1999).

Many smallholder farmers in SSA, practicing mixed farming, rely on manure to maintain soil fertility and to enhance crop production. Manure has been long recognized as one of the most effective ways of improving soil fertility and crop production in tropical African conditions (Watts-Padwick, 1983). It has been adequately demonstrated that the application of manure can improve crop yields and soil properties (Probert *et al*., 1995; Kihanda, 1996). Manure improves soil biophysical and chemical conditions through acting as a precursor to soil organic matter, adding nutrients to the soil, providing carbon (the source of energy for soil biota that regulates nutrient cycling), influencing nutrient mineralization-immobilization patterns and reducing soil phosphorus sorption of the soil (Müller-Sämann and Kotschi, 1994; Palm *et al*., 1997). Manure also improves biological properties of the soil and reduces trace element deficiencies (Arakeri *et al*., 1962; Tamaka, 1974; Flaig, 1975; Dalzell *et al*., 1979). Manure moderates soil temperatures and its continued use can progressively improve soil cation exchange capacity, exchangeable bases (K, Ca and Mg) and buffer soil pH (Grant, 1967). In the semi-arid areas of Eastern Kenya, Kihanda and Warren (1998) found that the addition of manure increases Olsen P, the increase being proportional to the rate of manure applied.

Given the low application rates of inorganic fertilizers, a study on manure utilization as a complementary source of inorganic fertilizers is considered highly relevant. Few studies exist on determining quantities of manure available at farm level and their relative quality in different agro-climatic zones and under varying farmer livestock management systems in SSA (Lekasi *et al*., 2003; Rufino *et al*., 2006). The few available studies have indicated that quantities of manure at farm level are often inadequate to maintain soil fertility and crop yields (Palm *et al*., 1997). Furthermore, few studies exist on quantities of nutrients (from manure and other inputs) applied by smallholder farmers to arable land, at plot and farm level and farmers strategies for coping with limited available inputs across different soil fertility gradients (Rowe *et al*., 2006).

In this study, manure production, quality and use among smallholder farmers were investigated in two contrasting livestock management systems in the sub-humid and semi-arid areas of Kenya. Semi-structured questionnaires were used to capture smallholder farmers' manure management practices and their potential for nutrient losses while a decision support tool, monitoring of nutrient flows and economic performance in tropical farming systems (NUTMON), was used to quantify livestock numbers and to explore manure use and crop nutrient supply at farm level. In addition, manure quality was determined using laboratory analyses. The specific objectives of the study were:

- To give insight into smallholder farmers' manure management practices and their potential implications on manure quality and nutrient losses;
- To determine the quality of on-farm available manures across different livestock management systems and agro-climatic zones and their implications for nutrient supply and crop production;
- To investigate the potential manure production and supply under different livestock management systems and
- To explore opportunities and constraints of smallholder farmers' current fertilisation practices and nutrient supply for crop production.

MATERIALS AND METHODS

Description of Study Site

The study was carried out in two contrasting sites, Kiambu and Mbeere Districts of Kenya. Kenya is located at the East Coast of Africa bordering Indian Ocean to the South East, Somalia to the East, Ethiopia to the North, Sudan to the North West, Tanzania to the South West and Uganda to the West with the Equator dividing the country into almost two equal halves. The annual rainfall in Kiambu District, Central Kenya, ranges from 600 to 2000 mm, depending on location and altitude, with an average of 1200 mm in the study site. The District has two main rainfall periods viz. long rains (March-May) and short rains (October-December). Crop and dairy (livestock) production are practiced. The common dairy cattle breeds kept are Friesian, Ayrshire, Guernsey, Jersey and their crosses. The dairy animals are confined in stalls and fed by cut-and-carry system (zero-grazing). Other livestock kept in the district include poultry, pigs, sheep, goats, rabbits and bees. Manure from livestock is used to fertilize crops, which include maize, Irish potatoes, vegetables, coffee, bananas and fodder. The land is intensively cultivated and is cropped 1.4-1.7 times per year (Jaetzold and Schmidt, 1983). Milk from dairy cattle is a major cash earner in the district.

Kiambu district has a population of approximately 744,010 persons and 189,706 households (CBS, 2001). The district is densely populated (Table 1). The farmers in the district enjoy a greater comparative advantage over most farming regions in Kenya. The combination of suitable climate, well-developed infrastructure and proximity to the country's main market, Nairobi, makes Kiambu district the most economically vibrant in the country and puts the district on a competitive edge. Approximately 70% of the population in the district rely on the agricultural sector (dairy and crop farming) for their livelihoods through direct or indirect employment. The district's prevalence of rural food poverty is estimated at 24% while rural food poverty gap and absolute poverty are estimated at 6.2 and 25%, respectively (MoFP, 2000).

Annual average rainfall in Mbeere District, Eastern Kenya, is relatively low and unreliable. Rainfall is bimodal, namely, long rains (March-May) and short rains (October-December). Subsistence crop-livestock farming is practiced and crops grown include maize, beans, cowpeas, sorghum, sweet potatoes and cassava. Indigenous breeds of cattle, goats and poultry are kept under open grazing system. Livestock graze in open pastures and fallow land during the day and are corralled at night. Manure from livestock is used for fertilising crops.

Mbeere district has a population of 170, 953 persons and 37,036 households (CBS, 2001). The district is sparsely populated (Table 1). The road network, postal and telecommunication services are inadequate and underdeveloped. Agriculture and off-farm activities employ 92 and 7% of labour, respectively. The district's prevalence of rural food poverty is estimated at 57.4% while rural food poverty gap and absolute poverty are estimated at 20 and 51.4%, respectively (MoFP, 2000).

Farm Selection and Characterisation

Farmers who participated in this study were part of an on-going project Integrated Nutrient Management to Attain Sustainable Productivity Increases in East African Farming Systems (INMASP). INMASP uses farmer field school approach in stimulating learning and development of technologies on integrated nutrient management practices. A representative catchment within each administrative district was selected, after which 30 farm households per district were included in the research (Table 2). The thirty households in Kiambu formed Kibichoi Farmer Field School (FFS) while a similar number in Mbeere formed Munyaka FFS. Kibichoi FFS (in Kiambu district) and Munyaka FFS (in Mbeere district) are located in Kiratina and Nthawa Locations, respectively (Fig. 1). The selected study sites in Kiambu and Mbeere Districts represented sub-humid and semi-arid agro-climatic zones, respectively. The actual selection process commenced with a workshop for the whole

Table 1: Characteristics of study site in Kiambu and Mbeere Districts

Characteristic	Kiambu	Mbeere
Geographical position	Latitude 0°75' and 1°20' South Longitudes 36°54' and 36°85' East	Latitudes 0°20' and 0°50' South Longitude 37°16' and 37°56' East
Total district land size (km^2)	1324	2093
Altitude (meters above sea level)	1200-2550	500-1200
Average rainfall (mm)	600-2000 (1100-1200*)	550-1100 (800-900*)
Rainfall pattern	Bimodal (relatively reliable)	Bimodal (unpredictable/unreliable)
Temperature	13.5-21.9°C	20-30°C
Population density (persons km^{-2})	562	82
Arable land (% of total district land size)	97	81
Contribution of smallholding to total land holdings (%)	99	98

Secondary data at District level (CBS, 2001; Jaetzold and Schmidt, 1983; Kassam *et al*., 1991); *: Figures in parenthesis are specific to locality of the study site within the district.

Table 2: Characteristics of studied farms in Kiambu and Mbeere Districts (mean values with standard deviation in parenthesis)

Characteristic	Kiambu (Kibichoi Wimenye FFS)	Mbeere (Munyaka FFS)
Agro-climatic zone	Sub-Humid	Semi-Arid
Number of households	30.0	30.0
Household size	6.3 (2.4)	6.5 (1.8)
Labour units (aeu)[a]	3.4 (1.4)	3.2 (1.3)
Total farm area (ha)	0.8 (0.5)	1.4 (1.2)
Cultivated area (ha)	0.8 (0.5)	1.2 (0.8)
Distance to the market (km)	6.1 (1.0)	10.6 (1.9)
TLU[b]	4.0 (5.1)	1.1 (1.7)
TLU ha^{-1}	6.0 (7.7)	1.0 (2.0)
Households below poverty level (%)	80.0	100.0
Farming practiced	Rainfed (mixed farming)	Rainfed (mixed farming)

[a]: aeu: Adult equivalent units; [b]: Tropical Livestock Units (1 TLU = 250 kg live weight); : Poverty level: 1 US$ a day (poverty level calculated based on family earnings)

community in the selected representative catchment aiming at discussing the objectives, creating ownership of the study and discussing criteria for participation namely, land size, livestock ownership and rainfed farming. Other criteria used were willingness to participate in the study, willingness to share information with others and geographical location of the farm within the target catchment.

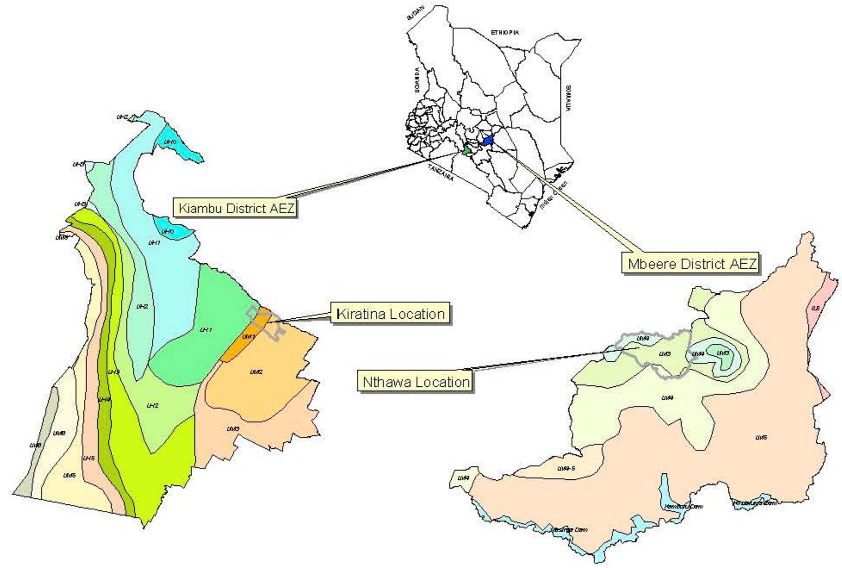
Household sizes were comparable across agro-climatic zones and mirrored national averages for rural areas (Table 2). The total number of livestock per farm and livestock density in Kiambu was higher than in Mbeere. The high poverty levels observed in both sites are likely to be influenced by low rainfall and poor farm performance during the period of monitoring. In general poverty level in Mbeere is higher than in Kiambu.

The soils in the Kiambu study site (catchment) are well drained, deep to extremely deep, dusky red to dark reddish brown, friable clay in places with humic acid topsoil, Humic Nitisols. They are moderate in organic C and total N, but low in extractable P. In Mbeere study site, the soils are well drained, shallow to deep, yellowish brown, loamy sand to sandy loam, Luvic Arenosols. They are strongly acid to slightly acid and low in organic C, total N and extractable P (Muya, 2003).

Farmers' Manure Management Practices and their Implications for Nutrient Losses

A study of smallholder farmers' manure management practices and their potential for nutrient losses was carried out using a semi-structured questionnaire (baseline questionnaire) administered to the selected household heads in a one time recall interview. The questionnaire captured information on livestock housing characteristics; manure collection; manure storage and application methods and constraints to manure use and farmers coping strategies.

Data collected on livestock housing characteristics were the presence of a roof, concrete floor, animal beddings and slurry drain in the housing pens. Manure collection and storage methods



Main zones	0	1 (I)	2 (II)	3 (III)	4 (IV)	5 (V)	6 (VI)	7 (VII)
Agro-climatic zones (ACZ)		Humid	Sub-humid	Semi-humid	Semi-humid to semi-arid	Semi-arid	Arid	Very arid
Agro-ecological zones (AEZ)	Perhumid	Humid	Sub-humid	Semi-humid	Semi-humid to semi-arid	Semi-arid	Arid	Perarid
TA	TA0	TA1	TA2	TA3	TA4	TA5	TA6	TA7
UH	UH0	UH1	UH2	UH3	UH4	UH5	UH6	UH7
LH	LH0	LH1	LH2	LH3	LH4	LH5	LH6	LH7
UM	UM0	UM1	UM2	UM3	UM4	UM5	UM6	UM7
LM	LM0	LM1	LM2	LM3	LM4	LM5	LM6	LM7
L	L0	L1	L2	L3	L4	L5	L6	L7
IL	IL0	IL1	IL2	IL3	IL4	IL5	IL6	IL7
CL	CL0	CL1	CL2	CL3	CL4	CL5	CL6	CL7

Source: Adapted from Sombroek *et al.* (1982) and Jaetzold and Schmidt (1983)

UM2: Sub-humid (Upper Midlands) zone
UM4: Semi-humid to semi-arid (Upper Midlands) zone
TA: Tropical alpine zones (annual mean temperatures 2-10°C)
UH: Upper highland zones (annual mean temperatures 10-15°C)
LH: Lower highland zones (annual mean temperatures 15-18°C)
UM: Upper midland zones (annual mean temperatures 18-21°C)
LM: Lower midland zones (annual mean temperatures 21-24°C)
L and IL: Lowland zones and Inner Lowland zones (annual mean temperatures >24°C; mean maximum >31°C)
CL: Coastal lowland zones (annual mean temperatures >24°C; mean maximum <31°C)
SUD: Sudan
UG: Uganda
TAZ: Tanzania
SOM: Somalia

Fig. 1: Location of the study sites in Kiambu and Mbeere Districts of Kenya

investigated were *in situ* storage or accumulation of manure in housing pens before being transported to crop fields; removal of manure from housing pens, heaping or storing manure elsewhere before application to crop fields and manure heap management methods (covering, storing under shade and composting). The study also investigated methods used by farmers to apply manure to various crops as well as constraints farmers face in using manure.

Determination of Manure Quality

Manure samples, for laboratory analysis, were collected from seven randomly selected farmers from the 30 study farms in Mbeere and from 30 farms in Kiambu, respectively in December 2004 (2004 short rains). Sampling of manure was done by scooping from four random spots on manure heap in each of the selected farms to a depth of 30 cm (Zhang *et al*., 2001). At time of sampling, manure heap was considered by farmers to be ready for application to crops. The four samples were mixed together thoroughly and a composite sample of approximately 1 kg taken. The composite sample per farm was placed in a plastic bag, labelled and transported to the laboratory the same day.

The manures were air dried and then ground to pass through 2 mm screen openings. A wet digestion method followed by colorimetric determinations was used to measure total N and total P (Novasamsky *et al*., 1983; Okalebo *et al*., 2002). The exchangeable cations (Ca, Mg and K) were extracted with NH_4OAc solution followed by flame photometry for determination of K and by atomic absorption spectrometry for determination of Mg and Ca (Okalebo *et al*., 2002).

Determining Potential Manure Production and Nutrient Supply

Livestock manure production was estimated from livestock numbers (measured in tropical livestock units) in the study sites and equations and transfer functions derived from secondary data sources that relate manure production to livestock types and livestock numbers (Table 3). The calculations were made on dry matter basis and did not take animal beddings and or feed refusals into account. Data on livestock numbers were collected using nutrient monitoring model as described in the subsequent section on farmers' current practices on manure use and crop nutrient supply. The calculated manure production was used to estimate potential manure application rate i.e. the possible quantity of manure that can be applied to a unit area of arable land suppose farmers were to spread manure uniformly in all parts of their farms (uniform manure application over total farm area).

Farmers' Current Practices on Manure Use and Crop Nutrient Supply

Monitoring of nutrient flows and economic performance in tropical farming systems (NUTMON) decision support tool was used to quantify livestock numbers and to explore manure use and crop nutrient supply at farm level. NUTMON toolbox comprises a set of manuals and questionnaires that are used for data collection and computer software for data entry and processing (Vlaming *et al*., 2001a, b). Data on livestock numbers, manure use and crop nutrient inputs were collected from the

Table 3: Assumptions made in estimating potential manure production in Kiambu and Mbeere study sites

Assumption	Source
A ruminant produces 0.8% of its live weight as faecal dry matter per day	Fernández-Rivera *et al.* (1995), Lekasi *et al.* (2001)
Adult birds (poultry) produce 500 g of fresh manure (70% moisture content) per year per kg of body weight.	FAO (2004)
Pigs produce about 1.05-3.45 % of total live weight as faecal DM (manure) per day; dry matter fraction of 0.299; A figure of 2.25% of total live weight faecal DM per day was used in this paper.	Matthies and Bossel (s.a) DM fraction figures from Hopkins and Cruz (1982)
An adult rabbit (non nursing) produce 40-80 g fresh manure per day with dry matter of 40-50% depending on quantity and quality of feed. In the study, a rabbit with a TLU of 0.01 was assumed to produce 40 g fresh manure per day (manure dry matter of 45%)*.	FAO (1986), Varenne *et al.* (1963)

*: Body weight of common adult rabbits range from 2.5 to 4.5 (FAO, 1986); TLU = 250 kg live weight of an animal; DM = Dry matter

60 study farms (spread equally over Kiambu and Mbeere) using two NUTMON questionnaires, namely inventory and monitoring questionnaires. The inventory questionnaire was administered at the beginning of the agricultural season alongside the baseline semi-structured questionnaire for capturing farmers manure management practices. The inventory questionnaire captured the following livestock data: livestock type (cattle, goats, pigs, sheep, poultry, rabbits etc.), livestock breeds (indigenous, exotic, cross breeds etc.) and livestock management systems. The monitoring questionnaire was administered at the end of the agricultural season (six months later) to capture growth and composition of livestock and dynamic livestock management practices, in retrospect. It also captured data on quantities of manure and inorganic fertilisers used by farmers for crop production and the specific plots/fields within the farm in which they were applied. Farmer's local units of measurements (for manures and inorganic fertilisers) were calibrated, into kg, by weighing them using a spring balance. The specific portions (fields/plots) of the farm receiving different nutrient inputs were demarcated and measured using a tape measure and their areas (in m^2) determined. The collected data were processed using NUTMON software and then further analysed using statistical software, SPSS 12 for Windows (SPSS, 2003).

RESULTS AND DISCUSSION

Manure Management and Implications for Nutrient Losses

Manure management and system of raising animals, including livestock housing, influences manure quality and quantity. In Kiambu, livestock are permanently confined (zero-grazing) in housing structures, bomas, with roofs (Table 4). In Mbeere, livestock are raised under open systems (free range), but corralled at night with a lower number of cattle owners (29%) housing them in kraals (traditional boma) with roofs and or partial roofs than goat owners (82%). This implies that only limited manure, especially from cattle, is collected in kraals with roofs and partial roofs in Mbeere.

Chicken and rabbits are kept in housing structures with roofs in both study sites. Presence of a roof in a livestock housing structure reduces manure nitrogen loss through leaching during rainy periods while the opportunities for collecting manure in zero-grazing units are higher than under free range systems (Lekasi *et al*., 2001). However, limited studies exist on the effects of different kraal roof types on N, P and K losses in livestock systems of sub Saharan Africa.

In Kiambu, the use of concrete floor and slurry drains was reported in 50 and 43% of the 30 study farms, respectively. They were not reported in Mbeere. Well covered slurry (mixture of dung and urine) pits help to minimize urine and manure nitrogen and potassium losses while the use of concrete floors in zero-grazing units, that contain livestock fed on supplements, has been associated with improved manure P and Ca contents (Lekasi and Kimani, 2003). Also hard flooring has been reported to reduce N losses through leaching (Rufino *et al*., 2006).

In Mbeere, where livestock are corralled at night, most of the urinary nitrogen is predisposed to volatilization and leaching losses since the use of animal beddings and concrete floors are limited (Table 4). The percentage of farmers using animal beddings were, however, higher in Kiambu than in Mbeere. Nitrogen and potassium leaching/accumulation, up to depths of 0.5 m, have been recorded beneath cattle kraals in Eastern Kenya (Probert *et al*., 1992). Animal beddings can reduce ammonia losses by 40-85% (Mohamed Saleem, 1998; Nzuma and Murwira, 2000) during manure storage (*in situ* in the kraal or otherwise). Reports by Camara (1996) have also shown that the use of litter in animal corralling sites reduces nitrogen loss in West Africa. Furthermore studies conducted by Lekasi *et al*. (2003) have also demonstrated that addition of animal beddings results in low mineral N (reduced possibilities for N loss) compared with manure from animals kept without bedding.

In the open grazing systems of Mbeere, animals graze outside cropping fields during the day (implying a potential manure loss) and within the farms after crop harvests (manuring done *in situ*).

Table 4: Livestock housing characteristics in Kiambu and Mbeere study sites

Description		Kiambu			Mbeere		
Livestock type	Housing characteristic	No. of farms	Percentage of total (n = 30)	Percentage of farms with livestock*	No. of farms	Percentage of total (n = 30)	Percentage of farms with livestock*
Cattle	Roof	24	80	100	2	7	29
	Concrete floor	15	50	63	0	0	0
	Slurry drain	13	43	54	0	0	0
	Use beddings on floor	13	43	54	1	3	15
Goats	Roof	15	50	100	23	77	82
Chicken	Roof	23	23	100	30	100	100
Rabbits	Roof	9	9	100	5	17	100

*: Calculated by considering number of farms with a particular housing characteristics and total number of farms owning a particular livestock type

Table 5: Farmers manure collection, storage, management and application methods in Kiambu and Mbeere Districts (percentage of households reporting)

	Percentage of farmers reporting[1]	
Manure collection and storage	Kiambu	Mbeere
Manure accumulation in kraal before direct transport to crop fields	33	81
Manure removed from kraal/*boma* and stored in a heap	83	40
Manure heap management		
Manure covered	20	10
Manure stored under shade (surface storage)	20	37
Composting manure before use	33	7
Methods of manure application		
Apply in furrows without covering with soil	17	3
Apply in furrows and cover with soil	73	50
Use hill or on-station method without covering with soil	60	NR
Use hill or on-station method and cover with soil	30	23
Broadcast without covering with soil	17	7
Broadcast and incorporate into the soil	17	37

NR: Not reported; [1]: Calculations based on total no. of households for each site: 30 households

However, each day the animals are corralled at night and there is a potential to collect manure from the animal pens (kraal or boma) for crop production. This management system results in less excreta N deposited in the kraal, at night, than the total N excreta deposited in grazing fields during the day. A higher number of farmers in Mbeere leave manure to accumulate in livestock *boma* than their counterparts in Kiambu, who remove manure on a regular basis and heap it besides the zero-grazing unit or cattle boma (Table 5). The manure removed from *boma* is accumulated (heaped) for sometime before application to crop fields. Heaping manure reduces its surface area and so decreases leaching compared with uncollected manure (Rufino *et al*., 2006). In Mbeere, manure is removed from cattle boma less frequently (1-2 times a year) than in Kiambu (daily to once every two-three weeks), depending on cattle boma type (concrete floor, deep litter or soil floor etc) and farmers' management practices.

The long period of manure storage and accumulation in the livestock *boma* in Mbeere predisposes such manure to high nutrient losses through volatilization and leaching since the use of animal beddings and roofs in cattle bomas are limited. In Kiambu farmers use diverse organic materials either as beddings (in bomas without concrete floors) or deliberately add them onto manure heaps. These materials include feed refusals (leftovers), hedge prunings and crop residues among others. Once removed from the boma, manure is either directly transported to the field (81% of farmers in Mbeere) or heaped besides the boma, to dry and cool, before transportation to crop fields (83% of farmers in Kiambu). Long storage of manure and infrequent manure removals from livestock kraals have been found to induce nitrogen losses through leaching and volatilisation of between 8-40% especially when manure is not covered (Kirchman, 1985). A low proportion of farmers (20-37%) in this study covers their manure heap and or store manure under shade. Manure, which is uncovered is exposed to wetting and drying conditions and is thus predisposed to nutrient losses. Nutrient losses, through volatilisation, are likely to be higher in the warm sunny weather of Mbeere than in Kiambu (but may be high in Kiambu as well, depending on contents of ammonia N among other factors). Studies by McCalla (1975) have reported that up to 50% nitrogen is lost after 4 days of manure storage without cover. Other studies have also shown that potassium losses (through leaching) of up to 50% can occur when uncovered manure is exposed to rain (Anonymous, 1996).

Composting can be an essential strategy in enhancing the quality and stability of manure, but N losses can be high depending on composition of composting materials. Losses of N occur in labile N pools and are thus more likely when there is a high proportion of labile material in the compost heap. The percentage of farmers practicing composting was low, but comparatively higher in Kiambu (33%) than in Mbeere (7%). These farmers compost their manure in either shallow pits (pit composting) or by heaping manure on the ground surface (surface composting) without additives. Additives such as rock phosphates, bone meal, mineral fertilisers, livestock urine, green plant materials and crop residues, wood ash and herbal preparations among others have a potential to improve manure quality (Müller-Sämann and Kotschi, 1994). However, the addition of urine to manure does not have a significant effect on nutrient concentration as most of it is lost through volatilisation (Lekasi *et al*., 2003).

Composting manure in deep pits or under anaerobic conditions minimizes ammonia losses. In a study by Thomsen (2000), manure composted aerobically lost 46% of its total N after 86 days of storage, whereas anaerobically composted manure lost only 18%. Other studies have shown that when manure is stored or composted in deep pits for 4-6 months, its nitrogen content may increase up to 3 times that of similar manure type stored or composted above ground surface without additives (Musa, 1975; Nzuma and Murwira, 2000). Manure stored under anaerobic conditions tend to produce organic acids that leads to a lower pH ($pH<7$) and therefore reduced losses of N via volatilisation (Kihanda and Gichuru, 1999). Composting manure under aerobic conditions leads to increased N mineralization (thus potential high N) and to concentration of mineral N by decomposition of C (Lekasi *et al*., 2003).

A higher percentage of farmers in Kiambu (73%) apply manure in furrows and cover it with soil than farmers in Mbeere (50%). In Kiambu, the practice is popular for Irish potato (*Ipomea batatas*) production while hill application (on-station, spot or hole application) is the preferred method for cereals (especially maize), vegetable and fruit production. In Mbeere, manure is applied in furrows made by oxen ploughs and then covered with soil after sowing. The method is popular for cereals and pulses. However, a higher percentage of farmers in Kiambu (about 17%) than in Mbeere (3-7%) apply manure in furrows without covering and or broadcast manure without soil incorporation. Similarly, about 60% of farmers in Kiambu do not cover manure with soil when manure is applied to some crops such as Napier (surface application). This exposes manure to vulgaries of weather and predisposes it to nutrient losses through volatilization and leaching.

Manure use in Kiambu and Mbeere is constrained by its inadequate availability and the labour required to transport and apply it (Table 6). The high labour demand has been corroborated with other studies, which have reported that applying organic inputs requires additionally high labour input for transporting and incorporating the materials into the soil (Ruhigwa *et al*., 1994). Another limitation in using manure is white grubs. The white grubs, larvae of many species of beetles in the scarab family (Scarabaeidae), reported in Mbeere (associated with uncomposted manure) were believed to be damaging young crop seedlings.

Due to inadequate availability of manure, farmers have adopted different coping strategies (Table 6). Manure is applied in rotation and in different spots on the farm according to perceived

Table 6: Reported constraints to manure use and farmers coping strategies in Kiambu and Mbeere Districts (percentage of farmers reporting)

	Percentage of farmers reporting	
Description	Kiambu	Mbeere
Constraints to manure use		
Inadequate manure	63	60
Inadequate labour	23	27
Expensive to purchase	10	**
Inadequate beddings	7	NR
Inadequate livestock feed	7	NR
Incidences of white grubs	0	33
Coping strategies with inadequate manure		
Manure applied in rotation	87	80
Purchasing manure	20	0
Using beddings	43	3

NR: Not reported; **: Manure not traded in the site; n = 30

Table 7: Cattle manure quality in Kiambu and Mbeere districts (minimum and maximum values in parenthesis)

Chemical indices	Kiambu (n = 7)	Coefficient of variation (%)	Mbeere (n = 6)*	Coefficient of variation (%)
Nutrient content (% DM)*				
N	1.41 (1.05, 1.88)	22	1.22 (0.63, 1.75)	40
P	0.53 (0.35, 0.99)	47	0.29 (0.08, 0.32)	31
K	1.54 (0.86, 2.1)	33	2.14 (1.27, 4.33)	52
Ca	0.45 (0.03, 1.89)	156	0.35 (0.02, 0.95)	103
Mg	0.38 (0.15, 0.73)	53	0.38 (0.18, 0.70)	61

*: DM = Dry matter; **: One manure sample dropped out of the analysis due to contamination

spatial and temporal variability in soil fertility and perceived importance of the crop. The percentage of farmers using crop residues as beddings to increase manure quantity was higher in Kiambu (43%) than in Mbeere (3%) while 20% of studied farms in Kiambu reported manure purchases to supplement on-farm available manure. There were, however, no manure purchases in Mbeere. Farmers consider purchasing manure to be expensive since it involves direct cash outlay.

Manure Quality at Farm Level

Manure quality is the value of manure in improving soil properties and enhancing crop yields. Chemical indices, which have been used to determine manure quality, include nutrient contents (total N, P, K, Ca and Mg), C-to-N ratio, ash content, lignin (%), polyphenols (%) and soluble fractions of N, P and C and acid detergent fibre nitrogen (Kihanda and Gichuru, 1999; Palm *et al*., 1997; Nhamo *et al*., 2004). The chemical quality of manure (at time of field application) from Kiambu was higher than that from Mbeere in a number of chemical indices (Table 7). This could be, partly, attributed to relatively better manure collection and storage, livestock management and feeding systems and manure management strategies.

In Mbeere, nutrient contents of manure are low as manure is derived from open grazing systems where animals are hardly fed with feed supplements. Studies have shown that manure having high N and P contents can be obtained when animals are fed with feed supplements and young forage (Jama *et al*., 1997; Delve *et al*., 1999; Lekasi *et al*., 2001). Nitrogen losses through leaching and volatilisation are probably high, as well, in Mbeere because manure is collected in open systems that are susceptible to leaching (during rains) and ammonia volatilisation.

It was not clear why potassium contents of manure in Kiambu were lower than that from Mbeere. However, the digested, but not utilized surplus soluble nutrients, like potassium are mainly excreted in urine from where it is susceptible to leaching losses when there are poor collection and storage methods (Snijders and Wouters, 2003). Although the ash content of manure was not measured in this study, it is expected to be higher for manures from Mbeere than from Kiambu, resulting in low C and nutrient contents. This is because the manures from Mbeere are likely to be contaminated with sand floor of the open animal pens (kraals). In itself, soil contamination does not reduce the total amount of N in manure, but it is associated with conditions that promote N loss through leaching, which further reduces the fertilizer value of the manure (Rufino *et al*., 2006). In a study by Probert *et al*. (1995), in Eastern Kenya, total N contents of manure ranged from 0.23 to 0.70%, but ash content was in the range of 79-94% because of contamination with soil from the floor of the kraal. Similarly, in smallholder farms of Zimbabwe, Nhamo *et al*. (2004) reported total N contents of manure to be 0.4-1.2% while ash content ranged from 27-92% due to soil contamination.

Variability in manure quality was high within and across study sites with higher N, K, Ca and Mg variability observed in Mbeere than in Kiambu. There are several probable causes of variability in manure quality, namely, quality of feeds, type and age of animal, methods of manure collection and storage, degree of sand contamination resulting in variable ash contents, addition of beddings and other additives and manure application methods among others (Somda *et al*., 1995). Similar variability in nutrient contents of farmyard manure has also been reported elsewhere in Kenya and other countries (Table 8). These reports tend to indicate that poultry manures and manures from dairy farms have higher quality than most manure found in open cattle grazing systems (Mugwira and Mukurumbira, 1984; Palm *et al*., 1997).

There has been limited success in applying plant quality indices to the accurate prediction of manure mineralization, partly due to presence of glucosamine (muramic acid) polymers derived from microbial cell walls among other factors (Devele *et al*., 2001; Rufino *et al*., 2006). However, a critical range of total N in organic materials is estimated to be 1.6-2.5%, below which nitrogen immobilisation occurs (Palm *et al*., 1997; Snapp *et al*., 1998; Kihanda and Gichuru, 1999; Okalebo and Woomer, 2003). Nitrogen contents of manures reported in this study (Table 7) were below these critical levels thus can temporarily cause nitrogen immobilization (resulting in non availability of N to crops initially). Organic materials with a P content of less than 0.25% immobilize P (Blair and Boland, 1978). The average P contents of some manure samples in Mbeere were below these critical values and could therefore, initially, immobilise soil phosphorus.

Table 8: Nutrient contents of farmyard manure collected from Kenya and other countries

Source	N	P	K	Ca	Mg
	----------	----------	(%)	----------	----------
Cattle manure in dryland eastern Kenya					
Onduru *et al.* (1999)	0.39	0.10	0.63	NR	NR
Probert *et al.* (1995)	0.23-0.70	0.08-0.22	0.28-1.14	0.58-2.02	NR
Probert *et al.* (1992)	0.17-1.28	0.08-0.45	0.26-2.65	0.58-1.94	NR
Goat manure in dryland eastern Kenya					
Kihanda *et al.* (2004)	1.89	0.47	3.72	NR	NR
Cattle manure from sub-humid central Kenya					
Lekasi and Kimani (2003)	1.12 (0.33-1.91)	0.31 (0.06-0.75)	2.39 (0.43-7.0)	0.26 (0.0-1.34)	0.51 (0.05-1.19)
Lekasi *et al.* (2001)	1.4 (0.5-2)	0.6 (0.2-1.6)	1.3 (0.5-2.7)	NR	NR
Woomer *et al.* (1999	1.4	0.2	2.38	NR	NR
Kihanda (1996)	1.19	0.24	1.46	0.87	0.26
Cattle/farm yard manure from other countries					
Tanzania, (Jackson and Mtengeti (2005) (kraal manure)	1.13	0.19	1.16	NR	NR
Harris (2002) (West Africa)	0.3-2.2	0.04-0.92	0.4-1.2	NR	NR
Zimbabwe (Mugwira (1984)	0.6-1.3	0.1-0.2	0.7-1.0	0.2-0.3	0.1-0.2
Africa (Defoer *et al.* (1998)*	0.5-2.3	0.22-0.81	0.77-5.44	NR	NR
Africa (Defoer *et al.* (1998)**	1.5-2.5	0.2-0.6	1.5-2.0	NR	NR
Other manures from sub-humid central Kenya (Woomer *et al.* (1999)					
Cattle *boma* manure	1.40	0.20	2.38	NR	NR
Poultry manure	3.11	0.42	2.40	NR	NR
Goat/sheep manure	1.48	0.20	3.31	NR	NR
Pig manure	1.40	0.23	2.02	NR	NR

[1] NR: Not reported; *: Without litter incorporation; **: With litter incorporation

Table 9: Livestock characteristics in Kiambu and Mbeere study sites

	Kiambu (Kibichoi FFS)		Mbeere (Munyaka FFS)	
Livestock type	Mean TLU	Percentage of total	Mean TLU	Percentage of total
Cattle	3.61 (4.98)	90.70	0.60 (1.65)	57.14
Goats	0.13 (0.16)	3.27	0.39 (0.24)	37.14
Sheep	0.06 (0.14)	1.51	0.00 (0.00)	0.00
Pigs	0.14 (0.77)	3.52	0.00 (0.00)	0.00
Poultry (chickens, ducks, geese, turkey)	0.03 (0.04)	0.75	0.05 (0.04)	4.76
Rabbits	0.005 (0.09)	0.25	0.009 (0.02)	0.95
Total	3.97 (5.11)	100.00	1.05 (1.65)	100.00

TLU = 250 live weight of an animal

The manure K contents in this study were above the K critical levels (modified Olsen K levels = 0.2 cmol K kg^{-1} soil or $\geq$ 0.0782% K-total) for most crops in Kenya (Gikonyo *et al*., 2000). This implies that they can be used to supplement K in K-deficient soils. The potential for manure to supplement K in K-deficient soils have been demonstrated by long term studies in Kabete, Kenya, where application of manure decelerated the rate of K depletion (Kanyanjua *et al*., 1999; Kapkiyai *et al*., 1999). Other studies have also shown that application of manure at 5 ton ha^{-1} meets maize K demands on some Kenyan Humic Nitisols (Gikonyo and Smithson, 2004).

Estimating Manure Production and Potential Nutrient Supply

The quantity of manure available to a farmer depends on many factors, namely, the types and numbers of animals, amounts and quality of feeds, watering regime, the spatial and temporal distribution of livestock and their voidings in the landscape and management system (pen rearing, kraaling the animals at night, or free range) and the efficiency of manure collection (Powell and Williams, 1995). Livestock types and their numbers (measured in tropical livestock units) in the study sites are shown in Table 9. A tropical livestock unit (TLU) represents 250 kg live weight of an animal.

Ruminant livestock (cattle, goats and sheep) accounted for about 95% and 94% of total livestock (in TLUs) in Kiambu and Mbeere study sites, respectively. They also accounted for about 90 and 98% of the total manure production in Kiambu and Mbeere study sites, respectively. However, cattle alone accounted for a higher total estimated manure production in Kiambu (86%) than in Mbeere (60%).

We calculated a higher potential livestock manure production in Kibichoi FFS, Kiambu (0.7 ton dry matter TLU^{-1} $year^{-1}$) than in Munyaka FFS, Mbeere (0.62 ton DM TLU^{-1} $year^{-1}$) (Table 10). Expressed per farm basis, these figures translate to 3.1 and 0.7 Dry Matter (DM) $year^{-1}$ $farm^{-1}$ for Kiambu (Central Kenya) and Mbeere (Eastern Kenya), respectively. The low levels of manure production in the semi-arid areas of Eastern Kenya has been corroborated by previous studies that estimated manure production to be 1 ton DM livestock $unit^{-1}$ $year^{-1}$ (Probert *et al*., 1995). Similarly, Strobel (1987) has estimated manure production under zero-grazing conditions in Kenya to be 1-1.5 ton DM $animal^{-1}$ $year^{-1}$.

Given the potential manure production at farm level, we calculated average potential manure application rates of 1149 kg DM ha^{-1} $year^{-1}$ $farm^{-1}$ and 725 kg DM ha^{-1} $year^{-1}$ $farm^{-1}$ in Kiambu and Mbeere study sites, respectively. The variation between farms was, however, large as shown by high standard deviation (Table 10). The application rates translates into 3.3 and 2.1 ton fresh weight manure ha^{-1} $year^{-1}$ $farm^{-1}$ in Kiambu and Mbeere, respectively based on 35% dry matter in manure. The calculated low rates of manure availability for Mbeere, Eastern Kenya, is corroborated by earlier studies in some parts of Eastern Kenya that reported figures of 2.5 ton fresh weight manure ha^{-1} annually (Ockwell *et al*., 1991; Probert *et al*., 1995). However, the calculated potential manure

Table 10: Potential manure production in kg DM $year^{-1}$ from the available livestock in Kiambu and Mbeere study sites (mean manure production with standard deviation in parenthesis)

	Kiambu		Mbeere	
Per animal type	Mean manure production (kg DM $year^{-1}$)	Percentage of total	Mean manure production (kg DM $year^{-1}$)	Percentage of total
Large ruminants (cattle)	2632 (3637)	86.0	438 (1206)	59.8
Small ruminants (goats and sheep)	137 (168)	4.5	286 (177)	39.1
Pigs	287 (1574)	9.4	0 (0)	0.0
Poultry	1 (2)	0.0	2 (1)	0.3
Rabbits	3 (6)	0.1	6 (15)	0.8
Total manure production	3060 (3920)	100.0	732 (1203)	100.0
Cattle manure production TLU^{-1}	729 (0)		730 (0)	
Total manure production TLU^{-1}	771 (250)		618 (179)	
Per farm				
Potential manure application per farm (kg DM ha^{-1} $year^{-1}$)	1149 (756)		725 (749)	

DM = Dry Matter

Table 11: Fertiliser (organic and inorganic) application in Kiambu and Mbeere over a half a year period (mean values with standard deviation in parenthesis)

	Kiambu		Mbeere	
Nutrient source	Farm	Field/plot	Farm	Field/plot
Organic fertilisers				
Farmyard manure (kg DM ha^{-1})	3161 (4397)	7581 (9617)	214 (319)	2297 (5845)
Household waste (kg DM ha^{-1})	366 (376)	3458 (6355)	411 (552)	3391 (5494)
Sub-total (organics) (kg DM ha^{-1})	3527 (4483)	11039 (13139)	625 (816)	5688 (7602)
Inorganic fertilisers				
CAN (kg ha^{-1})	5.6 (15)	23.5 (60)	0.1 (0.4)	0.3 (2)
DAP (kg ha^{-1})	29.4 (35)	120.4 (206)	2.7 (6)	4.3 (10)
NPK (17-17-17) (kg ha^{-1})	54.2 (91)	121.2 (228)	6.7 (28)	6.8 (28)
NPK (20-10-10) (kg ha^{-1})	4.2 (23)	21.9 (120)	0.0 (0)	0.0 (0.0)
NPK (23-23-0) (kg ha^{-1})	1.1 (6)	2.0 (11)	0.0 (1)	0.0 (0.0)
Sub-total (inorganics) (kg ha^{-1})	94.0 (115)	289.0 (487)	9.0 (28)	11.4 (29)

DM = Dry Matter; Dry matter farmyard manure = 35%; Dry matter household waste = 80%

application rates for Kiambu was within the range of 0.5-10.2 t DM ha^{-1} $year^{-1}$ for medium farms of 0.7-1.8 hectares reported in previous studies in Central Kenya (Lekasi *et al*., 2001).

Farmers' Current Practices on Manure and Inorganic Fertiliser Use

Farmers in the study sites use diverse manure types, mostly from cattle, to fertilise crop fields. These are collectively referred to as farmyard manure (FYM). The rate of application of FYM, household waste and inorganic fertilisers to crop fields were expressed in two ways, viz, (i) quantity of manure per hectare per half a year of the fields/plots actually receiving manure (field/plot scale) and (ii) quantity of manure/inputs per hectare per half a year averaged over the total farm area (farm scale) (Table 11). At farm scale, farmyard manure application rates varied highly across study sites with average application rates in Kiambu being 14 times that of Mbeere for each hectare of cropping land. This was probably due to higher livestock numbers (and therefore higher manure availability) in Kiambu than in Mbeere as well as due to the fact that farmers accumulate manure over time before field application. The latter enabled farmers, for example in Kiambu, to achieve higher application rates, in any one given application frequency, than what is potentially possible as calculated earlier.

The average FYM application rates per farm of 3.2 ton DM ha^{-1} (≈ 8.9 ton Fresh weight, FW, ha^{-1}) in Kiambu was moderate. Studies in Kenyan highlands have indicated that manure application rates vary from 0 to >17.5 tonnes Fresh Weight (FW) ha^{-1} with an average of 11 tonnes

FW ha^{-1} (Lekasi *et al*., 1998; Makokha *et al*., 2001). The FYM application of 0.2 ton DM ha^{-1} (≈ 0.6 ton FW ha^{-1}) in Mbeere (semi-arid) was below the often high recommended application rates of 10 to 15 ton FW ha^{-1} year^{-1} for semi-arid areas (Grant, 1981). The FYM application rates in Mbeere were also lower than 5-8 tonnes FW ha^{-1} year^{-1} required for meeting maize and millet/cowpeas nutritional demands in Eastern Kenya (Ikombo, 1984; Kihanda and Warren, 1998). Thus, although manure is an important nutrient source, it is insufficiently available for whole farm application in a single cropping season.

At plot scale, farmers in Kiambu and Mbeere applied manure at higher application rates than what was potentially possible in a single agricultural season, given the number of livestock available at farm level and potential manure production (Table 10, 11). This was because the farmers in Kiambu (as well as their counterparts in Mbeere), do not apply FYM to the whole farm in a single cropping season, but accumulate manure over a period of time for any application frequency and then apply it in designated fields/plots on a rotational basis.

The FYM and other soil fertility management inputs (household waste and inorganic fertilisers) are judiciously applied to specific crops, on smaller portions (fields/plots) of land rather than spread thinly over the whole farm in a single cropping season. Field plots close to the homestead also receive higher application rates than fields further away (spatial manure application). This has been corroborated with other studies in Western Kenya (Tittonell *et al*., 2005). The farmers are therefore able to create hot spots in designated field plots in the farm and over several seasons spread manure in the entire farm. These practices result in higher FYM application rate in selected fields/plots within the farm than when the same quantity of FYM were to be spread uniformly across all fields/plot and in the whole farm (Table 11). The measured FYM application rates at field/plot level, namely, 21 ton FW ha^{-1} in Kiambu (≈ 7.6 ton DM ha^{-1}) and 6.6 ton FW ha^{-1} in Mbeere (≈ 2.3 ton DM ha^{-1}) were, however, lower than 40 ton ha^{-1} reported in similar studies at field/plot scales in some parts of Kenya (Probert *et al*., 1992; 1995). Depending on the time intervals and quantity of manure applied, the efficiency of high manure applications can be questionable. Studies in Zimbabwe have shown that small frequent applications of manure to a maize-legume rotation results in greater N uptake efficiency in the first and second season after application than the recommended practice of applying 35-40 tonnes manure ha^{-1} once every 4 years (Nyamangara *et al*., 2003).

The concentration of FYM and other organic wastes in fields close to the homestead and to specific crop fields within the farm creates on-farm gradients of soil fertility, with distant fields and less valuable crops receiving less nutrients and low intensity of management. This leads to nutrient depletion in parts of the farm and in distant fields as well as crop yield gradients (Ruthenberg, 1980; Tittonell *et al*., 2005). Studies have shown that it is inefficient to concentrate manures or fertilizers on small parts of the field close to the homestead, especially if their application (manures/fertilizers) causes available nutrients to exceed what can be used by crops (Rowe *et al*., 2006). However, once the soil fertility gradients are created and the distant fields become degraded (decline in soil organic C), then it is best to apply fertilizers to the more fertile soils for higher nutrient use efficiency, as long as crop requirements are not exceeded. This is because the use efficiency of added nutrients decreases as soil organic matter declines (as in the degraded distant fields) below a certain threshold.

The application rates for inorganic fertilisers to cropping land followed a similar trend to that of FYM with higher rates used in Kiambu than in Mbeere (Table 11). Farmers in central highlands of Kenya (e.g., Kiambu), probably due to dairy farming and cash crop activities, have relatively higher opportunities for cash income and therefore higher purchasing power for inorganic fertilisers than their counterparts in the semi-arid Eastern Kenya (e.g., Mbeere) who are mainly subsistence farmers (Mose, 1998). Similarly, economic returns to crop production in Kiambu tend to be higher than that in Mbeere making it economically attractive to invest in fertilizers in Kiambu. The inorganic fertiliser application rates in Mbeere were low and less than 10 kg ha^{-1}, a figure often reported for sub-Saharan Africa (Yanggen *et al*., 1998).

Table 12: Phosphorus inputs supplied by farmers for crop production in Kiambu and Mbeere over a half a year period (mean with standard deviation in parenthesis)

	Phosphorus (kg ha^{-1})			
	Kiambu		Mbeere	
Nutrient source	Farm	Field/plot	Farm	Field/plot
Organic sources				
Farmyard manure	20.7 (31.0)	48.0 (61.5)	0.6 (1.1)	5.6 (15.1)
Household waste	0.4 (0.4)	3.5 (6.4)	0.4 (0.6)	3.4 (5.5)
Sub-total (organics)	21.1 (31.1)	51.4 (63.7)	1.0 (1.6)	9.0 (15.7)
Inorganic sources				
CAN	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
DAP	6.2 (7.4)	25.3 (43.3)	0.6 (1.2)	0.9 (2.1)
NPK (17-17-17)	4.0 (6.7)	9.0 (16.8)	0.5 (2.1)	0.5 (2.1)
NPK (20-10-10)	0.2 (1.0)	1.0 (5.3)	0.0 (0.0)	0.0 (0.0)
NPK (23-23-0)	0.1 (0.6)	0.2 (1.1)	0.0 (0.0)	0.0 (0.0)
Sub-total (inorganics)	10.5 (11.4)	35.4 (59.4)	1.1 (2.2)	1.4 (2.8)
Grand total	31.6 (33.1)	86.8 (92.6)	2.1 (3.6)	10.4 (16.4)

In this study, phosphorus inputs have been used to illustrate quantities of nutrients supplied by farmers for crop production in the study sites based on their current practices (Table 12). Phosphorus is one of the most limiting nutrients for crop production in the two study sites (Muya, 2003). Livestock manure (FYM) was the dominant source of nutrients for crop production in the study sites and was used as a sole application or in combination with varying quantities of inorganic fertilisers. Farmyard manure accounted for a higher total P supply to crops in Kiambu (55-66%) than in Mbeere (29-54%). This could be due to higher manure P contents and application rates in Kiambu than in Mbeere. However, when household waste are also considered, then Mbeere farmers tended to rely more on organic inputs (FYM + household waste) for P supply to crops (accounting for 59-87% of total P supply) than their Kiambu counterparts where FYM + household waste accounted for 48-67% of total phosphorus supply.

The total supply of nutrients from inorganic and organic sources in Mbeere were below the recommended rates of 30-50 kg P_2O_5 ha^{-1} (13-22 kg P ha^{-1}) for the staple food crop maize in the marginal areas of Eastern Kenya (MoARD, 2002; KARI, 2004). This further confirms that the current manure and inorganic fertiliser application rates among smallholder farmers in Mbeere are inadequate to meet staple food crop nutrient demand and could be one of the contributing factors to low crop yields observed at farm level. However, P supplied by farmers for crop production in Kiambu was moderate compared with the recommended rates of 50-60 kg P_2O_5 ha^{-1} (22-26 kg P ha^{-1}) for maize crops in some parts of Central Kenya (KARI, 2004). However, it has to be noted that nutrient release from manure is slower than from commercial inorganic fertilizers, not all manure-nutrients are released in the first season of application, the residual effects of previous manure applications can contribute to crop production in the subsequent seasons and crop response to applied nutrients is dictated by soil nutrient deficiencies and the rate at which nutrients from manure are made available (Müler-Sämann and Kotschi, 1994; Kihanda and Gichuru, 1999). Also under low soil pH, as in Kiambu study site, phosphorus fixation is expected (Muya, 2003).

Given slow nutrient release from manures, high labour demand for transportation and low quantities of manure available at farm level, the use of manure should essentially be a part of an Integrated Nutrient Management (INM) strategy that considers combined use of organic and inorganic nutrient sources for sustainable crop production (Graves *et al*., 2004). In the INM, strategy, focus should not only be on P, but also on N, K, organic C and other limiting nutrients. Farm practices that address N through biological fixation (legumes) should essentially address soil P deficiencies, as well, since biological N fixation is limited by low soil P among other factors (Giller *et al*., 1997; Smithson and Giller, 2002).

In both study sites, strategies for enhancing soil fertility using either sole application of organic nutrient sources (FYM + household wastes) or inorganic nutrient sources (inorganic fertilisers) seems limited in providing a comprehensive solution to crop nutrient supply. Similarly, current smallholder farmer's strategies to combine organic inputs with limited quantities of inorganic inputs seem inadequate in supplying nutrients for improved crop productivity. Crop yields at farm level are still far below their potential, partly, because of inadequate quantities of nutrients added, the low quality of organic materials used and inappropriate or inefficient combinations of organic and inorganic nutrient sources.

This study had several limitations. The study relied on a small sample size and on farmyard manure N, P, K, Ca and Mg contents to give an indication of quality, but neither took into account nutrients released in urine (when collected separately) and commonly used quality parameters such as C-to-N ratios nor parameters such as ash content, net nitrogen mineralization rates or modifiers of N release patterns such as lignin and polyphenols. These indices are increasingly becoming important in determining nutrient release patterns, quantities of manure to be applied, manure application frequencies and in designing a rotational manure application strategy. The study also identified possible nutrient loss avenues during manure collection, storage and handling among smallholder farmers, but did not measure these nutrient losses at farm level. Data on nutrient losses during manure management are limited in sub-Saharan Africa and there is need to develop techniques for measuring manure nutrient losses at farm level as well as devise manure handling techniques that minimise such losses, especially in systems with high manure fluxes.

CONCLUSIONS

Manure management among smallholder farmers in the sub-humid and semi-arid areas of Kenya is variable and often poor irrespective of whether livestock are raised under confinement (zero-grazing) or in open systems (free range). Poor housing, unsound manure collection and storage and poor manure application methods potentially predisposes such manure to nutrient losses. The measurement of these nutrient losses and the designing of affordable strategies to reduce them would be important in bridging nutrient gaps and enhancing crop and livestock productivity. Such strategies should also be assessed for their economic and agronomic viability, for example, does the labour required to implement the strategies translate into additional nutrient supply and economic gains?

On-farm available manure in the semi-arid areas, where open grazing is practiced without feed supplementation, is poorer in quality (low N and P and possible contamination of manure with soil) than manures from sub-humid areas where animals are raised under confinement with feed supplementation. The low quality manures can potentially immobilise N and P, making them unavailable for crop uptake. Improving manure quality in the open grazing systems will among others, require improving livestock nutrition with N and P rich feed supplements, improving manure collection and storage methods in the night kraals and adopting strategies for reducing nutrient losses during manure storage, transportation and application.

The study has shown that the quantity of manure available at farm level varies with agro-climatic zones, livestock management systems and methods of collection and is low in semi-arid areas. In practice, nutrient losses during manure collection, storage and application in sub-humid and semi-arid areas lower manure use potential. Therefore, strategies for improving manure quality, improving manure use efficiency, integrating the low quality manures with inorganic sources and or integrating legumes in farming systems where manure is used, among others, are needed to improve crop nutrient supply.

Given the limited availability of farmyard manure, costly inorganic fertilizers and differences in household resource endowments in the sub-humid and semi-arid areas and between farms, separate strategies need to be developed for each agro-ecological zone (and farm resource-endowment class) to assist farmers optimally manage the available soil fertility inputs. Such strategies should take cognisance of (i) the necessity of designing effective and efficient manure handling and storage systems, including techniques that reduce losses after manure excretion (improving roofs and floors of kraals, changing from aerobic to anaerobic composting etc.); (ii) the need to quantify on-farm available manure and nutrient inputs and outputs at each farming sub-system for improving nutrient use efficiency; (iii) full costs and benefits of newly proposed practices and technologies and how such practices fit within the farming system; (iv) spatial variability in soils and soil fertility in fields close to and distant from homesteads; (v) residual effects of manures of varying quality, applied sole or in combination with inorganic fertilizers; (vi) spatial and temporal benefits and limitations of current farmers practices of applying manure in a rotational pattern; (vii) improving the synchrony of N mineralization and crop uptake; (viii) developing simple farm decision-making tool for estimating manure quality and (ix) integrated soil fertility management strategies that recognize synergistic and complementary effects of organic and inorganic nutrient sources and farmers socio-economic settings in technology development and adoption.

Despite generating interesting results, the study had several limitations including reliance on a small sample size and use of manure nutrient contents as quality indicators without considering modifiers of nutrient release patterns such as lignin and polyphenols. Studies that involve large sample sizes and that integrate these indices holistically are therefore required to bridge knowledge gaps on current manure quality and application frequency across different livestock and manure management systems. The study also did not measure manure nutrient losses, although nutrient loss avenues were identified. Future studies, that take into account these limitations, are required to enhance knowledge and understanding of manure availability, quality and its use in various agro-climatic zones and under diverse smallholder farmers socio-economic circumstances.

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