CORNELL UNIVERSITY GRADUATE SCHOOL

APPROVAL OF THESIS/DISSERTATION

Name of candidate: Helen Ann Markewich

First Name | Middle Name | Family Name

Graduate Field: Animal Science

Degree: Ph.D.

Title of Thesis/Dissertation:

Dairy cattle feeding and manure management on smallholder farms in Kenya

COMMITTEE SIGNATURES:

Chairperson: Alice N Pell Date: 1/20/2009

Member: Harold Van Es Date: 12/22/08

Member: [signature] Date: Dec 11 '08

Member: Debbie J. Cherney Date: 12/11/08

Member: ____________ Date: ________

Member: ____________ Date: ________

LICENSE TO USE COPYRIGHTED MATERIAL

(Student Signature)

DAIRY CATTLE FEEDING AND MANURE MANAGEMENT ON SMALLHOLDER FARMS IN KENYA

A Dissertation

Presented to the Faculty of the Graduate School

of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

by

Helen Ann Markewich

May 2009

BIOGRAPHICAL SKETCH

Helen Ann Markewich was born October 7, 1981 in Washington D.C., but grew up in Atlanta, Georgia and considers herself a Georgia Peach through and through. Her childhood was a very pleasant time filled with family, music, uncoordinated attempts at dancing, and dogs. The advent of a younger brother added cats, birds, baseball, and matchbox cars to the mix. High school passed in a blur of oboe-playing and horses. Undergraduate biology studies the Georgia Institute of Technology were very enjoyable years of late-night study sessions, laboratory mishaps, and plots to sneak pints of ice cream into the library, punctuated by cow-related summer internships. After a brief foray into the world of bacterial STI research at the Centers for Disease Control and Prevention in Atlanta in 2003, Helen turned with relief from human urine samples to cattle urine samples (which smell much better) when she accepted a place as a Ph.D. student with Dr. Alice N. Pell at Cornell University's Department of Animal Science. The years of coursework in Ithaca and fieldwork in Kenya have been marked by some major changes: Helen's interest in cows' diets morphed to an interest in their manure and the younger brother graduated to muscle cars. At the end of graduate studies, what is next?

Dedicated to my very loving, supportive, and patient family.

ACKNOWLEDGMENTS

Dr. Alice N. Pell, my committee chair and my committee members, Dr. Debbie J.R. Cherney, Dr. Johannes Lehmann, and Dr. Harold M. van Es offered guidance, valuable advice, and availability for meetings and discussions. Dr. David M. Mbugua was the best fieldwork supervisor I could ever have hoped for, being constantly available for advice, help, and Nairobi driving instruction, directions, and tips.

At Cornell, Dr. James B. Robertson cheerfully and patiently withstood onslaughts of questions about methods and concepts. Dr. Hugh G. Gauch's and Dr. Giles Hooker's statistical guidance was invaluable. Dr. Chuck Nicholson's attentive teaching style was an important lesson. Debbie A. Ross, Kathy K. Dusinberre, and Dr. Denis O. Molina were always available for laboratory help and advice, often at the spur of the moment. Terry B. Kinsman, Timm D. Lathwell, Susan H. Herbert, Deloris G. Bevins, Ginny L. Montopoli, and Bonnie Ferguson were always available for help, and were very receptive to panicked emails from abroad.

At the World Agroforestry Centre, Nairobi, Dr. Louis Verchot, Dr. Keith Shepherd, Dr. K.P.C. Rao, Margaret Thion'go, Mercy Nyambura, Robin Chacha, Valentine Karari, Andrew Sila, Elvis Weullow, Dickens Ateku, Vincent Mainga, Edith Anyango, Maurice Obunga, and Charles Kigwe offered scientific expertise and laboratory support.

At the World Agroforestry Centre, Maseno, Manoah Ombwayo, Janes Obando, Zablon Khatima, and Andrew Kibira offered dedicated help and field support.

At the Kenya Agricultural Research Institute (KARI)-Embu, Dr. Stephen Njoka, Dr. Macharia Gethi, Mr. Kagondu, Mr. David Kinga, Dr. Ngoroi, Ann Njeri, Samuel Gatonga, Martin Nyaga, Evans Namu, Susan Njoka, Eunice Ndwiga, Samuel

Njagi, Preston Ndwiga, Nelly, and all of the KARI-Embu staff offered endless guidance and support.

The staff of the University of Eastern Africa at Baraton dairy facility collected and sold their cattle manure at reasonable prices. The staff of the Maseno Veterinary Farm dairy facility generously offered their land, equipment, and cattle manure.

The farmers of Madzuu, Mukangu, and Manyatta who participated in the studies generously offered their time and knowledge to aid the research.

Gary R. Buell and Dr. Arthur J. Horowitz gave much needed help, guidance, and conversations about methods. Mamadou M. Chetima, Dr. Julie C. Frey, Dr. Florence V. Nherera, Dr. Solomon O. Ngoze, John W. Recha, Dr. James M. Kinyangi, Dr. Jane J. Kapkiyai, Dr. Paswel P. Marenya, and Lydiah W. Gatere offered time for wonderful discussions about Kenya, science, and everything else.

My friends Dr. Ripal B. Jariwala, Amy H. O'Neill, Risa J. Rivera, Jessica P. Grayson, Dr. Jessica M. Rothman, Dr. Barbara Szonyi, Dr. Roxann M. Weix, Dr. Kelly A. Butterworth, Dr. Evelyn M. Galban, Meagan A. Cooney, Joke Putseys, Dr. Tim P. McComb, Jen L. D'Amato, and Susan M. Gilchrist provided hours of fun and laughter and put everything in perspective.

Fred D. Markewich, William Markewich, Helaine W. Markewich, Elaine F. Walsh, Heather L. Walsh, and all of my family gave their endless support and love.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ADF	Acid detergent insoluble fiber
ADICP	Acid detergent insoluble crude protein
ADIN	Acid detergent insoluble nitrogen
BCS	Body condition score
C	Carbon
CH_4	Methane
CNCPS	Cornell Net Carbohydrate and Protein System
CO_2	Carbon dioxide
CP	Crude protein
CV	Coefficient of variation
DM	Dry matter
DMI	Dry matter intake
ME	Metabolizable energy
MP	Metabolizable protein
N	Nitrogen
NDF	Neutral detergent insoluble fiber
NDICP	Neutral detergent insoluble crude protein
NDIN	Neutral detergent insoluble nitrogen
NH_3	Ammonia
NH_4	Ammonium
NIRS	Near-infrared spectroscopy
NO_3	Nitrate
N_2O	Nitrous oxide
O	Oxygen

OM	Organic matter
P	Phosphorus
PCA	Principal components analysis
PCR	Principal components regression
SE	Standard error
SOC	Soil organic carbon
SOM	Soil organic matter

CHAPTER 1

LITERATURE REVIEW

Introduction

Environmental degradation associated with agriculture, a pervasive problem in many African countries, affects Kenya severely. High population growth during the past century in Kenya has forced the subdivision of farmland into increasingly smaller plots and thus the adoption of more intensive farming practices to produce sufficient food on smaller land areas (Ovuka 2000). These intensive farming practices include the shortening or the elimination of fallow periods, removing an important avenue of soil fertility replenishment (Conelly and Chaiken 2000). Such demanding use of soils can lead, over time, to severe nutrient depletion. Many Kenyan households with small farms and flagging soil fertility live in poverty and lack access to the resources and information to slow the degradation and improve the fertility of their land. Thus, poverty and environmental degradation are linked in a vicious cycle in which the dearth of resources and information inherent to poverty propagate the degradation process (Lee, Barrett et al. 2006). The degradation, in turn, leads to poor crop production and diminished incomes, planting households more firmly in poverty (Bationo, Kimetu et al. 2003).

In order to slow decreases in soil quality, amendments such as inorganic fertilizers, green manures, and livestock manure can be added to soils. When funds are available, farmers may purchase inorganic fertilizers. However, on many farms, soil nutrient and organic matter levels have fallen so low that the application of inorganic fertilizers will not stimulate crop growth enough to justify the fertilizer purchase (Marenya 2008). An inexpensive and effective means of replenishing soil nutrients and slowing land degradation is the application of livestock manure to soils.

Manure application is a means of retaining nutrients on a farm, thereby reducing the need for external inputs to renew soil fertility. Major nutrients provided by manure include nitrogen, phosphorus, and organic matter. The mineral N and organic, fiber-bound N contributed to the soil by manure (Zingore, Murwira et al. 2007) are the focus of this dissertation. Mineral N in the soil solution is available for uptake by plant roots. Organic N has the potential to be mineralized to mineral N forms (Havlin, Beaton et al. 2005). The addition of livestock manure to soil is a particularly sustainable method of preserving soil fertility on Kenyan smallholder farms since it requires no investment, initial capital, or external supplies other than the investment of labor. In largely zero-grazing systems, a portion of the nutrients of excreta and feed refusals, specifically N, is conserved in manure and returned to the soil of the same farm, not lost off-farm as is common in pastoral systems.

This review gives a brief history of soil degradation in Kenya, describes livestock ownership on smallholder farms, and explains the need for manure as a soil amendment to retain nutrients on-farm. The livestock ownership, housing, and manure management strategies common to smallholder farms are described. A description of feeding patterns is included, since the nutrition of the animal is inextricably linked to its growth, production, and manure quantity and quality. This is followed by an explanation of the effects of diet on the N composition of excreta of cattle. The dynamics of excreta N in storage, including a brief review of efforts to model manure storage systems, are then described. The decomposition of aged manure in soil is examined to complete the description of N dynamics. The topics covered in the review provide background for the two broad questions addressed in the dissertation: 1) Are the manure storage techniques currently in use on small farms in Kenya producing a soil amendment with a maximized mineral N content? 2) How variable is the diet fed to cattle on small Kenyan farms using the cut-and-carry system, and how does the diet variability affect dairy cattle production in these systems?

Land Degradation and Livestock on Small Farms in Kenya

History of land degradation in Kenya: Farming has been practiced in Kenya for many centuries. In central Kenya, there is proof of farming from 1000 A.D (Ambler 1988) and some suggest that agriculture may have been established many hundreds of years earlier during the late Stone Age (Spear 1981). Farming spread during the second millennium, C.E. and achieved status as the dominant livelihood in the 19^{th} century. Farmers in the highlands converted forest to agricultural land. The farming was often intensive (Spear 1981), but the approach to land conversion was one of extensive agriculture, meaning that when the population of a farmed area could no longer be supported by the resources of its land, new land was converted to agriculture (Ambler 1988). The prevention of soil erosion and conservation of water and fuel resources were not a priority in the farming systems (Ambler 1988).

Today, 57 % of land in Kenya is farmed: thirty-seven percent of the land is devoted to subsistence agriculture and 20 % is at the commercial scale (Kamoni, Gicheru et al. 2007). The population of Kenya continues to increase and soil degradation has emerged as a problem. Farming has intensified in order to produce enough food to sustain the population, but replenishment of soil nutrients has not kept pace (Cleaver and Schreiber 1992). The stocks of N, P, and K in soils are depleted (Jama, Swinkels et al. 1997; Onduru and Du Preez 2007). Using inorganic fertilizers to replenish the soil nutrients is expensive and may be beyond the means of many farmers (Cleaver and Schreiber 1992). It is possible, however, for soil nutrient levels and soil organic matter to fall so low that the application of inorganic fertilizers will not enhance crop growth enough to make the purchase of the fertilizer economically viable (Marenya 2008). Organic soil components are also declining, and soil organic carbon (SOC) stocks in Kenya are expected to decrease by between 34 Tg and 214 Tg of C by 2030 (Kamoni, Gicheru et al. 2007; Milne, Paustian et al. 2007).

Soil organic matter (SOM) and some inorganic nutrients may be replenished by the application of cattle manure to the soil (Mugwira, Nyamangara et al. 2002). Because they produce manure, cattle are a major source of nutrients on farms. Cattle manure, when applied to cultivated land, can improve crop growth and improve the efficiency of use of nutrients by the crops. Cattle manure is an organic soil amendment that adds several different nutrients to the soil environment, including N and P, improves the soil structure and physical characteristics, and increases SOM (Zingore, Murwira et al. 2007).

Livestock ownership, housing, and feeding on smallholder farms: Currently, the effects of land scarcity due to population pressure are keenly felt. In terms of land area, smallholder farms in the Central Province of Kenya deserve their name. In Maragua District, Central Province a mean farmland area of 1.8 ha and a range of 0.4 ha to 8 ha were reported (Lekasi, Tanner et al. 2003) in 1999. In 1997, 57 farms surveyed in Kiambu and Murang'a Districts, Central Province had a mean size of 1.56 ha with a range of 0.1 ha to 5.2 ha (Lekasi, Tanner et al. 2001).

These land constraints force farmers to use every possible square meter of their farm for crop production, thereby eliminating grazing spaces. Most smallholder farmers keep their animals confined near the farm house(s). The vast majority of farmers in Maragua District, 84 % in 1999, used an "improved boma" enclosure with a partial roof, solid floor and feeding trough. Less than 10 % of these farmers used either a true zero-grazing unit with a full roof, solid floor, distinct areas for feeding and lying, and separate feed and water troughs, or a "traditional boma" -- a small pen with deep litter underfoot and no shelter overhead (Lekasi, Tanner et al. 2003). The solid floors were most often built of hard-packed soil. Approximately two-thirds of the farmers in Kiambu and Murang'a confined their animals in true zero-grazing units while the remainder used the traditional boma. For the remainder of this dissertation, "improved bomas" and true zero-grazing units will together be referred to as zero-grazing units.

Forages are cut by hand and carried to the animals in zero-grazing units. The amount of feeds offered in cut-and-carry systems usually are not measured by weight or volume. The feeds offered to each animal on the farm are 'eyeballed' based on the total amount of forage available and the production level of the animal.

The combined effects of limited farmland area for forage production and the inexact nature of cut-and-carry feeding systems can result in poor cattle diets. The cattle of smallholder Kenyan farms consume diets with fairly low total N and available N concentrations (Nherera 2006). A study of cattle on smallholder farms in the Kenya highlands reported a mean daily dry matter intake (DMI) of 8.4 ± 2.4 kg, with 83.5 % - 90.2 % forage content and 61.2 % NDF content. The mean crude protein (CP) intake was 8.9 % of DMI during the dry seasons and 10.7% during the rainy seasons, with a mean rumen degradable protein intake of 60.5 % of CP intake that was not significantly different between seasons (Nherera 2006). Overall, the metabolizable protein in the diet provided 92 % or more of the daily requirements, but the 5.4 Mcal/day metabolizable energy deficit of the diet resulted in poor production of microbial protein in the rumen. Insufficient amounts of microbial protein traveled to the small intestines for post-ruminal absorption, so the cows were protein deficient (Nherera 2006).

Kenyan farmers value their livestock for their multiple roles. Cattle provide milk, meat, skins, and fiber for subsistence and for the market, transport, and a means to retain forage nutrients on the farm via manure. Additionally, the animals serve as a repository for savings: farmers invest in cattle when funds allow, then sell them when cash is needed, and benefit from the milk, manure, and transport in the interim (Mortimore 1998). Cattle purchases are constrained by funding: many cash-strapped smallholder farmers can afford to purchase an animal only occasionally. Cattle ownership is also constrained by feed availability. Land area limits the amount of forage that can be produced on-farm and purchasing feeds is very costly. So, most farms do not accumulate large herds of cattle. For example, smallholder farmers in Central Kenya typically own no more than three cows at one time. The herd sizes, though small, may still exceed the amount of available forage (Nherera 2006). In 1999, the cattle in Maragua were pure Holstein-Friesian (HF), Ayrshire, or cross-breeds with the local *Bos indicus* animals (Lekasi, Tanner et al. 2003). In addition to HF, Ayrshire, and their crosses, uncrossed local animals and Guernseys were found in Murang'a and Kiambu Districts in 1997 (Lekasi, Tanner et al. 2001). On small farms in the area around Embu, in Eastern Province, Kenya there was, on average, one mature dairy cow per farm at any time (Nherera 2006). The cows were housed in zero-grazing units with feed troughs, water troughs, and a partial roof. Thirty percent of the enclosures included a solid floor, bedding, and were cleaned daily, while the remainder had unfinished floors and were cleaned sporadically (Nherera 2006).

Regulation of Feed Intake: The amount of feed consumed daily by cattle depends on the amount of time needed to chew feed (Allen 2000), the volume of feed the animal can physically consume, the influence of concentrate feeds on intake (Jarrige, Demarquilly et al. 1986), and the rate of passage of feed through the digestive system (Conrad, Pratt et al. 1964). This physical control of intake is modified by nutrient absorption (Allen 2000). Energy dense, easily digestible concentrates can affect intake through chemical signals regulating energy intake by the animal (Jarrige, Demarquilly et al. 1986). When cattle are fed high forage, low concentrate diets, physical control of intake is dominant. When cattle consume highly digestible diets with few bulky forages, intake is mainly controlled by chemical regulation (Allen 2000). Dietary NDF, as a component of forages that contributes to their bulkiness, is used as a predictor of intake. Production stage and metabolic body size also contribute to intake regulation, especially when cattle consume highly digestible diets (Conrad, Pratt et al. 1964). On smallholder Kenyan farms, diets consist largely of poor quality forages (Nherera 2006). Physical control will likely be the major factor in the regulation of the intake of these forage-based diets.

If poor quality diets in early lactation are anticipated, feeding higher energy diets prior to parturition may prevent a decline in milk quality in terms of milk protein and milk fat in the subsequent lactation (Agenas, Burstedt et al. 2003). The energy density of the diet should be increased with concentrate feeds or high quality forages, since voluntary intake falls in late pregnancy and remains depressed during early lactation. This drop in intake is the result of a combination of physical, endocrine, and metabolic effects (Ingvartsen and Andersen 2000). After the initial decline in intake, the intake then increases throughout the first 6 to 10 weeks of lactation. In mid- and late lactation, intake decreases for cows fed digestible, high concentrate diets. The mid- and late lactation intake levels remain relatively constant for cows fed high forage, more poorly digestible diets (Friggens, Emmans et al. 1998).

N in Cattle Diet and Excreta

In ruminants, excess dietary N is excreted in the urine, and variation in feed N composition means that urinary N content is quite variable. From 50 % to 90 % of urinary N may be excreted as urea (Bussink and Oenema 1998). The non-urea urinary N includes uric acid, creatine, creatinine, allantoin, and hippuric acid, with a small fraction excreted as NH_3, amino acids, hypoxanthine, and xanthine (Bussink and

Oenema 1998). Elevated urinary N levels occur as the amount and availability of dietary N increase (Van Soest 1994). Because it is the repository of excess dietary N, urine volume and composition can a key variable in the N composition of cattle excreta collected for use as a soil amendment. Urea-N in the urine is easily volatilized, however, so steps must be taken to retain the urinary N in the manure before it is applied to the soil.

Fecal N content is much less variable than urinary N, since fecal N does not depend as heavily on the rumen-available N in the feed. Fecal N comprises 6 % to 8% of the crude protein (CP) content of the diet, except in animals suffering extreme N deficiencies or in those consuming diets of excessively high N content (Van Soest 1994). Diets containing large amounts of indigestible protein, such as mature tropical forages with large amounts of acid detergent insoluble N (ADIN), will produce feces with more CP because the refractory N passes from the animal intact. A less important source of fecal N is indigestible microbial biomass that was not degraded post-ruminally and was not absorbed in the small intestine. Fecal N also originates from keratin in skin and hair that has mixed with manure, and from proteins in cells of the digestive tract that have sloughed off during the passage of digesta and passed from the animal in the feces (Van Soest 1994).

It is estimated that European breeds of cattle excrete 75 g of N per kg of fecal dry matter (Tamminga 1992). Much of the fecal N is undegraded plant N. Indigestible feed N compounds are largely in the acid-detergent insoluble N (ADIN) fraction and are unavailable to rumen microbial degradation by their association with lignin and refractory fibrous compounds. Tannins in plants may also be a source of undegraded plant N. Some tannins bind protein and render the N unavailable to the animal (Van Soest 1994). Condensed tannins in the diet significantly reduce urinary N and increase the amount of undigested forage N in the manure (Misselbrook, Powell et al. 2005). Since the undigested plant N is often quite slowly available for mineralization by soil microbes and many tropical forage legumes contain tannins, much of the manure N produced by tropical animals may be slowly degraded in the soil.

Poor-quality cattle diets containing high levels of ADIN result in feces high in indigestible feed N. The tannin-bound and lignin-bound nitrogenous compounds in the ADIN cannot be degraded by rumen microorganisms, and pass from the animal intact. Kenyan cattle, consuming low-quality, high-NDIN and high-ADIN forages produce feces with significant ADIN content. A study in the Kenya highlands showed that the NDIN of the forages consumed ranged from 4.3% to 8.0% of total N while the ADIN ranged from 1.2 % to 4.2 % of total N (Nherera 2006). In order to fully understand the contributions of animal feces to soil N, it is important to measure the magnitude of the fiber-bound fecal N fractions, both NDIN and ADIN, and the rate at which these N forms are mineralized during manure storage and after the manure has been applied to soil.

N Dynamics in Manure Storage Systems

Introduction / Composting manure vs. stockpiling manure: The manure composting process of manure includes two phases: a thermophilic phase and a mesophilic phase. The first, thermophilic stage is characterized by temperatures between 45 °C and 70 °C (Mathur, Owen et al. 1993). Microbial respiration is rapid as the microbes degrade the many labile organic compounds in the manure (Mathur, Owen et al. 1993). During this stage, NH_4 is the primary mineral N compound produced by the mineralization of organic N compounds. The reactions involved in respiration produce heat that increases the temperature of the system (Mathur, Owen et al. 1993). The thermophilic stage generally lasts for the first thirty days of manure storage. The second, mesophilic stage is marked by a drop in temperature to between 28 °C and 40 °C as the compost matures (Mathur, Dinel et al. 1993; Mathur, Owen et al. 1993; Ulén 1993). The pools of substrates susceptible to microbial degradation decrease and microbial respiration rates slow. The rate of NO_3 production increases during this phase as temperatures fall and the less heat-tolerant NO_3-producing microbes begin to flourish (Mathur, Owen et al. 1993). During the mesophilic stage, both temperature and the rate of microbial respiration stabilize so that the compost system can remain in this state for many weeks or months. A target C:N ≤ 20 during the stable state avoids the immobilization of soil mineral N that occurs when compost with a higher C:N is applied to soil. The stable manure material is predominately composed of organic compounds that are insoluble in water and only slowly biodegradable. Because manure includes plant material previously digested by the cow, the residual material primarily is composed of lignified compounds. Lignified material is further stabilized by O-radical humification processes (Mathur, Owen et al. 1993).

These phases occur in manure compost systems that are properly maintained. Nutrient content, moisture content, aeration, and the balance between rapidly degradable and slowly degradable C and N compounds are maintained by the judicious addition of dry, fibrous materials such as straw to the compost. Aeration may also be controlled by turning the compost. On many small farms in Kenya, management of stored manure is not adequate to permit composting to occur. Manure is typically heaped in a pile or pit and left alone. This stockpiled manure is rarely if ever turned. Bedding, feed refusals, and other plant material, including fruit rinds and tree branches, may also be added. Soil from scraping the animal pen floors during cleaning may be added if the pens have a dirt floor.

Stockpiled manure that has not yet reached a mature composted state benefits crops more immediately when applied at planting. Immature stockpiled manure contains more mineral N and mineralizable N compounds that are rapidly converted to mineral N forms than composted manure (von Fragstein 1995). Immature manure has large amounts of water soluble, pre-humic organic compounds. Some of this soluble OM is available for degradation by microbes in soil (Van der Hoek and Oosthoek 1985; Cegarra, Vazquez et al. 1987; Mathur 1991). Mature composts are poorly biodegradable, containing stable organic compounds that increase SOM, but are slowly mineralized in soil. Mature, composted manure improves soil fertility over the long-term, but does not directly benefit plant growth via mineral N supply in a single season. These short-term and long-term differences dictate differences in the situations when it is optimal to apply immature manure and when it is best to apply mature stored manure. For example, when legumes are planted in rotation in soil of pH > 5.0, ensuring high rates of N accumulation, soil organic matter (SOM) and soil structure improvement takes priority over increasing the mineral N pool (von Fragstein 1995). Mature composted manure, with its low mineral N content and large potential for increasing SOM is the better soil amendment in this case. When the mineral N deficit is large, when there is a high demand for mineral N by the crops, and/or when the growing season is short, increasing the mineral N pool is of more immediate importance than improving SOM. Immature, stockpiled manure provides more immediately plant-available nutrients, so it is the better choice for a soil amendment (von Fragstein 1995).

Bedding and feed refusals in stockpiled manure: One study showed that cattle manure mixed with straw lost 24.8 % of its initial N content to NH_3 volatilization while manure alone lost only 9.2 % during 2.5 months when piled in heaps (Dewes 1995). This observation is contrary to the idea that increasing the C:N of the manure material causes immobilization of available N, thereby decreasing the pool from which NH_3 might be produced and volatilized from the system. Adding dry fibrous material decreases the moisture content of the manure and increases air pore size. The increased aeration allows for an increase in aerobic microbial decomposition leading to an increase in the production of NH_3.

N losses from stockpiled manure: The mineral N in stored manure can escape the system via volatilization and leaching. Manure in storage loses N to leaching to a lesser extent than by gaseous evolution (Dewes 1995). Leaching losses of 2.5 % - 3.4 % of the initial N content and NH_3 volatilization losses of 24.8 % - 44.4 % of the initial N in cattle manure stored in piles for 177 days have been observed. Initial manure N content was a key factor in leaching and volatilization N losses. The loss rates increased with increasing initial manure N (Dewes 1995).

Ammonia volatilization rates and the NH_4 concentration of leachate from manure storage piles are highest at the beginning of the storage period. As the degradable N compounds in manure are consumed by microbes during storage, the rate of NH_4 production decreases and less NH_4 is available to escape the storage system in the leachate or to be converted to NH_3 gas. Some of the NH_4-N produced during microbial degradation of manure is incorporated into new microbial cells. The use of NH_4-N by the microbes contributes to the decrease in the rate of NH_3 volatilization and in the decrease in leachate NH_4 concentration (Dewes 1995). The leachate volume also decreases with time in storage. That the leachate N concentration decreases while the volume is also decreasing indicates that the rate of decrease in the amount of N being leached exceeds the rate of decrease in leachate volume (Dewes 1995).

Manure in aerobic storage loses much less N to leaching than to NH_3 volatilization. It has been observed that approximately 10 % - 20 % of the initial total manure N was lost from leaching (Martins and Dewes 1992). Approximately 47 % – 78 % of the initial total manure N was lost from NH_3 volatilization. More than 70 % of N losses through leaching took place during the first 10 days of storage. The total N concentration of the leachate depended on the total N content of the initial manure. Manure with greater initial N content generally produced leachates with larger N concentrations, although the ranges in measured N concentration were quite wide: up to a 5.6-fold difference between minimum and maximum concentrations for the same manure pile were observed (Martins and Dewes 1992). Leachate lost in the first ten days of storage contained largely NH_4-N (approximately 77 % – 98 % of total leachate N) and very little NO_3-N (approximately 0.1 % - 2 % of total leachate N). Organic N comprised the remainder of the leachate N (Martins and Dewes 1992).

After the first 10 days of storage, leaching recommenced when a manure pile was aerated. As the storage period continued, leachate NH_4 concentration fell while the NO_3 concentration increased, reflecting the aerobic decomposition process in the stored manure from which the leachate originated (Martins and Dewes 1992).

The initial N content of manure and the leachate composition are often reported in terms of total N only. While the observed relationship between initial total N and leachate N concentration is helpful for predicting leaching losses of N, the wide ranges in the concentration of leachates adds uncertainty to the predictions. Total N indicates nothing about the forms of N in leachate or its availability to plants. Comparison of the initial mineral N with the organic N content of a manure stock could reduce this uncertainty. Mineral N and the labile organic N leach more readily than refractory organic N. Thus, a single manure stock with a small refractory N pool and large initial mineral N and labile organic N fractions leaches more N than manure with a bigger refractory fraction.

Immobilization of N can decrease gaseous N losses from stored manure. Mineral N that is assimilated by microbes is unlikely to be converted to gaseous NH_3. Additions of residues with large C:N ratios increase this effect, though the lignin content must be carefully considered since lignin reduces immobilization and mineralization. Residues with large C:N ratios but low lignin contents have slow immobilization rates and a slow return of immobilized N to the mineral N pool in stored manure (Subair, Fyles et al. 1999). Gaseous ammonia is lost when the pool of mineralized N is not quickly immobilized (Subair, Fyles et al. 1999). The mineral N pool then remains low since most of its contents have been volatilized and any immobilized N is released very slowly. Residues with a greater proportion of their carbon content in more degradable forms than lignin produce immobilization rates and immobilized N release rates rapid enough to minimize NH_3 volatilization and to allow for the accumulation of mineral N in manure (Subair, Fyles et al. 1999).

Manure stockpiling techniques: Another, less well recognized route of N loss from stockpiled manure is runoff. Runoff can occur when manure stored in uncovered piles exposed to precipitation. Runoff losses differ from leaching losses in that runoff occurs from the surface of the exposed manure pile while leachate comes from the entire manure pile and emerges from the bottom of the pile. Rainfall on exposed manure storage piles increased the volume of leachate and decreased the leachate N concentration. Although rainfall has not been identified as a major source of leachate, the proportion of leachate from rainwater initially is small, but it increases with duration of storage (Dewes 1995). One study of manure storage systems recommended covering stored manure to prevent precipitation-induced N losses via leaching and the smaller losses due to runoff (Ulén 1993). However, N losses from covered piles due to leaching were similar to those from exposed piles in spite of the fact that the waterproof covers reduced water evaporation during respiration early during storage. Also, NH_3 volatilization increased when manure was covered (Dewes 1995).

Mixing or turning manure regularly helps maintain the aerobicity of stored manure, promoting the mineralization of organic N and the nitrification of NH_4 into NO_3 available for uptake by plant roots. In a study of large-scale, high DM, aerobic manure piles (> 1 tonne FW, 7.4 % – 17.2 % DM), most N losses occurred through losses of NH_3 (Martins and Dewes 1992). Cumulative NH_3 gaseous losses exhibit a S-shaped pattern during storage, reaching a zero net loss between 13 and 27 days after the start of the storage period (Karanja, Gichangi et al. 2005). Losses from escape of nitric and nitrous oxide gas (NO^- and N_2O) contributed very little to gaseous N losses from manure storage (Martins and Dewes 1992). The mineralization of protein N and fiber-bound N increased the NH_4 ion pool. In response, the pH of the system rose above pH 9.5, shifting the NH_4 - NH_3 equilibrium towards gaseous NH_3 production. The NH_3-N was irrevocably lost as the gas escaped (Martins and Dewes 1992). Turned manure has lower C:N ratios and nearly twice the mineral N content of manure that is not turned (Lekasi, Tanner et al. 2003).

Adding fresh material to manure storage piles incrementally rather than having one static pile with manure of the same age resulted in increased volatilization NH_3-N losses. Systems of a uniform age, however, lost solids linearly over time while the incremental systems experienced no net loss of solid mass (Bastyr and Powers 2001).

Another important manure storage technique is the active collection and conservation of cattle urine into the storage system. Reports of urinary N of pasture-fed dairy cattle as a percent of total excreted N (feces and urine) ranged between 70 % – 78 % of total N (Bussink 1992), though this value is diet-dependent. Although urine is often incorporated into the manure material, especially when cattle are enclosed in zero-grazing units, urinary nutrients can be lost before collection and during storage. To curtail losses of N through volatilization of NH_3, urine must be collected and stored to minimize NH_3 production. Urine also contains high levels of potassium, an essential soil nutrient (Lekasi, Tanner et al. 2001) which does not volatilize, but which may be lost if the urine-soaked manure is not managed properly. The use of crop residues as bedding in cattle holding areas reduced NH_3 volatilization by 80 % since the plant material absorbed the urine, preventing NH_3 production and escape (Nzuma and Murwira 2000). The plant material may also limit NH_3 production by increasing the immobilization of N by microbes. Crop residues may improve the potential for N mineralization in manure storage systems by maintaining an aerobic environment. Provision of oxygen to stored manure is essential as nitrification (NO_3 production from NH_4) requires oxygen. Also, anaerobic conditions favor denitrification, which results in substantial N loss through the production and escape of N_2 and N_2O (Murwira, Swift et al. 1995). Manure amended with crop residues tends to have lower mineral N (NH_4 and NO_3) contents and higher C:N ratios than unamended manure (Lekasi, Tanner et al. 2003), but this is likely due to an immobilization of N by microbes, not an inhibition of mineralization.

Existing models of manure stockpiles: Scientists are actively modeling the nutrient dynamics of manure-based farming systems. However, most models of manure systems focus on the nutrient dynamics of manure prior to its collection and then when it is applied to soil, not on the nutrient dynamics of manure in storage.

A model of anaerobic manure storage based on data from open-faced pits was developed with the goal of simulating N losses and identifying strategies to reduce these losses (Muck and Steenhuis 1982). Assumptions made in the model included:

1 Manure decomposition processes were anaerobic since the pit contents were not turned or mixed.

2 All of the N losses from the system were defined as the NH_3 volatilization from the surface of the pit. Each 1 cm-deep layer of manure in the pit was uniform in composition and NH_3 traveled through each layer by diffusion before reaching the manure surface. Therefore, the NH_3 travel rate was modeled following Fick's Law of diffusion.

3 Between 40 % and 50 % of the N in the manure collected was in the form of urea-N (Muck and Steenhuis 1982).

4 At the surface of the manure, NH_3 loss was dependent on concentration of NH_3, manure pH, ambient temperature, and wind speed. Urea hydrolysis occurred within the first day of storage if the ambient temperature was above freezing (Muck and Steenhuis 1980; Muck and Steenhuis 1982).

5 The mineralization rate of non-urea organic N after 24 to 48 hours in storage slowed and by 30 days was assumed to be negligible.

6 N losses decreased with decreasing manure pH and with an increase in the rate of addition of manure to the system.

Validation of the model using data sets from the laboratory and the literature determined that the model satisfactorily predicted N losses from open-faced manure pits. The validation was completed with data from American dairy systems in New York, Wisconsin, and Iowa (Muck and Steenhuis 1982). The model may be assumed to be intended for application to North American dairies.

A comparison was made of a previously published model to experimental measurements of N losses from the floors of freestall dairy barns in New York (Muck and Richards 1983). The model was designed to predict NH_3 volatilization and urea hydrolysis from freestall barn alleys. The model used a 4 hour time step, so the mineralization of organic N to NH_4-N was not accounted for. The experimental observations were made at shorter time intervals to measure the mineralization more closely (Muck and Steenhuis 1981; Muck and Richards 1983). When the ambient temperature exceeded 20 °C, very large N losses occurred from barn floors. The losses were higher than the losses predicted by the model. In the same study, large amounts of non-urea organic N in the feces and urine were mineralized to NH_4 within the first 24 hours after excretion if the environmental conditions were warm. The model poorly predicted N losses from the manure on the barn floors, largely because rates of mineralization of non-urea organic N compounds were not included. Should a conservative estimate of N losses from barn floors be needed, however, the model was recommended for use (Muck and Richards 1983).

The DAFOSYM model was designed to track N and DM movements during feed digestion leading to manure production by dairy cattle, collection, storage in an open pit, and application to soil (Borton and Rotz 1995). In these systems, the manure was liquid. Manure composition and quantity were calculated based on the 1988 NRC nutrient requirements for dairy cattle (Borton and Rotz 1995; National Research Council 2001). During collection, N losses were described as a function of ambient temperature with a pivotal temperature of 2.5 °C (Muck and Richards 1983; Borton and Rotz 1995). For the collection component of the model, the focus was on the uses and costs of electricity, fuel labor, and throughput capacity. The amount of volatile N at the start of storage was estimated as 35 % of the total manure N remaining after collection (Overcash, Humenik et al. 1983; Borton and Rotz 1995). During storage, the loss of N via volatilization was a function of the number of days in storage, manure loading rate, whether the manure was loaded into the tank at the top or the bottom, wind speed, and ambient temperature. The wind speed variable applied only to top-loaded systems. The loading rate in both top- and bottom-loading systems was inversely related to the NH_3 losses (Borton and Rotz 1995). If the loading rate into the pit exceeded 1 cm of manure per day, NH_3 volatilization rates were calculated by dividing the NH_3 content by the loading rate according to Muck and Steenhuis (Muck and Steenhuis 1982; Borton and Rotz 1995). Total N losses from manure loaded at the bottom rather than the top of the pit were less than from top-loaded manure because of the time required for the NH_3 to diffuse to the surface (Muck and Steenhuis 1982). The DAFOSYM model was determined to successfully simulate manure management systems in Michigan, with applications to farms in all of the United States (Borton and Rotz 1995).

Large-scale vs. small-scale manure storage systems: Most research into manure storage systems, both of an experimental and of a modeling nature, focuses on large-scale systems (i.e. livestock farms with 50 or more animals). Most of these large-scale farms are located in developed countries where the climate is temperate and the livestock diets are of a high quality and are fed in an organized regimen. Small farms in developing nations in the tropics with few livestock (less than 10 animals) and poor quality, highly variable diets manage a much smaller volume of manure than their larger Western counterparts. The composition of manure from small farms is highly variable because of fluctuations in livestock diets. Differences in temperature and rainfall patterns mean that there are differences in nutrient losses from tropical small farms and from larger farms in temperate areas. Most studies of manure storage on small farms in the tropics are not controlled studies. Rather, they monitor and sample storage systems on existing farms (Lekasi, Tanner et al. 2001). Because of this, the nutrient dynamics reported in these studies are dependent on many different variables, including storage duration, animal housing style, animal age and production level, the degree to which urine is collected and conserved in the manure, and the amount of bedding and feed refusals mixed with the manure. The large number of variables that affect manure storage and differences in storage structures and methods mean that some of the results from the observational studies are inconclusive or conflicting. Controlled studies of manure storage on these small farm systems have obvious drawbacks, the most important of which is that it is difficult to control variation in on-farm experiments. Controlled studies observing a subset of the possible variables may give more definitive insights into the nutrient dynamics of manure storage systems on small farms.

N Dynamics of Manure applied to soil

Decay series of manure N in soil: When manure is applied to soil, the mineral N (NH_4-N and NO_3-N) present in the manure may be taken up by plants immediately, if the timing of manure applications is synchronous with periods of plant nutrient uptake. Ammonium-N not taken up by plants may be lost via ammonia volatilization (Eghball, Wienhold et al. 2002), while nitrates may leach from the soil. Manure organic N may be mineralized in soil, maintaining the pool of mineral N available for plant uptake long after the initial application of manure (Eghball, Wienhold et al. 2002). Manure N mineralization can be measured *in situ* or in the laboratory. In studies of N mineralization in manured soil, periodic measurements of organic N and inorganic N in the soil typically are made over one or several seasons. The measurements may be made in field studies using the buried bag technique, resin cores, or in laboratory studies monitoring ^{15}N labeling in manured soils. N mineralization may be calculated using regression techniques. Agronomic studies which calculate N mineralization using crop N uptake data in N balance equations are also used to develop decay series in manured soil (Vigil, Eghball et al. 2002).

The rate at which manure organic N is mineralized varies with soil and environmental conditions and depends on the composition of the manure applied to soil (Vigil, Eghball et al. 2002). Soil moisture at or near field capacity produces the fastest organic N mineralization in manured soil. Mineralization rates fall with declining soil moisture content (Cassman and Munns 1980). Warmer temperatures result in more rapid mineralization of manure organic N (Eghball 2000). Non-composted manure may mineralize at up to twice the rate of composted manure because many of the more easily degradable manure organic N compounds that are lost during composting may be present in non-composted manure. For example, 40 % of total N was available from non-composted beef feedlot manure added to Nebraska, USA soils within one year of application, with 18 % of the total manure N available for plant uptake during the second year after application (Eghball and Power 1999). A decay series developed for dairy manure applied to soils in New York, USA estimated 21 % of manure organic N to be available to plant roots during the first year after application, and 9 %, 3 %, 3 %, and 2 % of the remaining organic N available during the second, third, fourth, and fifth years after application, respectively (Klausner, Kanneganti et al. 1994). The N contents of dairy cattle manures on smallholder farms in Kenya tend to be lower than dairy manures in the USA: 1.12 % N (Lekasi, Tanner et al. 2003) vs 1.8 % N (Klausner, Kanneganti et al. 1994). Should decay series for manure applied on smallholder African farms be developed, slower rates of N mineralization are likely. The organic N of manures on smallholder farms may contain more slowly degradable compounds such as cellulose and lignin than manure from US dairies because cattle on smallholder farms consume diets based largely on poor quality forages while US dairy cattle consume diets with more concentrate feeds and high quality forages. Smallholder farm manure N may be more slowly mineralized in soil because of its smaller total N content and larger proportion of slowly degradable organic compounds, which are degraded slowly in soil (Vigil, Eghball et al. 2002). In Niger, 3.1 % of manure N disappeared from manured soil within 17 weeks of manure application (Esse, Bueckert et al. 2001). If this rate is extrapolated to one year, the estimated loss of total N is 9.4 % during the first year after manure application. This decay rate is considerably slower than those reported for manure and soils in American soils. The manure from Niger cattle likely degraded so very slowly because it contained more slowly degradable compounds, originating from the poor quality forages in the Niger cattle diets, than the US dairy manure.

Microbial responses to manure amendments to soil: Manure amendments may slightly increase the microbial N content of the soil by the concurrent addition of fecal bacteria in the manure (Bittman, Forge et al. 2005). The survival of fecal bacteria in soils is poor, although their viability in soil is variable, lasting up to two months (Unc and Goss 2004). Although fecal bacteria that live only a brief time in the soil do not contribute significantly to the living microbial biomass, their membrane and internal contents are released and degraded upon lysis, and enter the soil mineral N pool or are assimilated by living bacteria. Manure that has been composted or stored before application to soil has microbial biomass, mostly of environmental or anthropogenic (e.g. feed refusals) origin rather from the original fecal populations.

Soils receiving multiple manure treatments over several years contain more labile organic N-containing compounds than unamended soil (Paul and Beauchamp 1989; Sørensen 1998). Gram-negative soil bacteria can thrive on these compounds and outcompete soil fungi. Soil fungi are far more competitive than soil bacteria at using lignin and other refractory organic compounds as substrates (Horwarth 2007). The SOM of unamended soils contains a larger concentration of the most refractory organic compounds than the amended soils. The proliferation of Gram-negative bacteria in manure-amended soils has been likened to the preferred growth of these species in rhizospheres in response to organic acid root exudates (Peacock, Mullen et al. 2001).

Although soil VAM and the hyphae of filamentous soil fungi stabilize macro-aggregates in soil (Tisdall 1982; Bethlenfalvay, Cantrell et al. 1999), manure application does not decrease aggregation in soil (Aoyama, Angers et al. 1999) in spite of the repressive effect on fungal growth by manure (Olayinka 2001). Manure application stimulates bacterial growth in soil. High production of exo-polysaccharide by the manure-stimulated soil bacteria contributes significantly to aggregate stabilization, and may compensate for the loss of fungal stabilization in the soil (Olayinka 2001).

During the first year following manure addition to a soil, microbial biomass levels increase, but are smaller than biomass levels observed between the end of the first and the third year of manure application. Presumably, this occurs because insufficient labile substrates from manure are provided in the first year. As refractory compounds in manure are degraded by soil biota, the pool of labile substrates grows. In a long-term study with manure applications at regular intervals, between the end of the first and third years after manuring began, the microbial biomass reached an equilibrium (Bittman, Forge et al. 2005). Microbial biomass in these systems is controlled by the consumption of bacteria by soil microfauna (protozoa, nematodes), whose growth is stimulated by manure fertilization (Bittman, Forge et al. 2005).

A method developed to assess decomposition patterns of leaf litter on forest floors, the litterbag technique (Crossley and Hoglund 1962), is used in this dissertation research to measure decomposition of manure in soil. Litterbags provide a means to easily collect samples while still allowing contact between the sample material and the soil system (Salamanca, Kaneko et al. 1998). In the litterbag method, the material to be studied is placed in mesh litterbags and placed at the soil surface or buried at the experiment site. Litterbags are commonly made of nylon or fiberglass mesh. Litterbags are usually square in shape, with side lengths ranging between 0.01 m and

0.5 m. The initial mass and composition of the material are assessed prior to burial. After a prescribed number of days, the bags are removed from the site and the composition of the contents is determined. Decomposition patterns are estimated using the differences between the initial and final composition of the material in the litterbags (Crossley and Hoglund 1962).

The degradation activities of soil mesofauna and macrofauna may be distinguished from microbial degradation processes when litterbags of different mesh sizes are used in the same experiment (Crossley and Hoglund 1962; Cortet, Gillon et al. 2002). A range of mesh sizes may be used to exclude soil fauna of different sizes or to allow them access to the litterbag contents (Cortet, Gillon et al. 2002). Soil insects in the mesofauna and macrofauna groups physically break the litterbag contents into smaller particles and consume microfauna such as fungi (Couteaûx, Mousseau et al. 1991). Small mesh sizes to exclude all fauna but the microorganisms may be no smaller than 50 μ so as to prevent the formation of artificial microclimates in the litterbag contents (Vossbrinck, Coleman et al. 1979; Bradford, Tordoff et al. 2002).

N dynamics and N immobilization in manure-amended soil: Three major processes of interest in manure amended soils are N mineralization, nitrification, and N immobilization. The N in organic compounds is released into the soil solution as NH_4 during microbial degradation processes. Ammonium is converted to NO_3 in nitrification. Nitrates are the mineral nitrogen form that is available to plants for uptake. If the system in N limited, microbes may outcompete plant roots for the available N in the soil solution, resulting in a shortage of N available to plants. Denitrification, the loss of N from the soil system via the production and escape of N_2O and N_2 gases, is another process of interest in manure amended soils. Denitrification is also addressed in this section.

Manure may reduce net nitrification in the first few weeks after the amendment in comparison with unamended soils, likely due to its accelerating effect on N immobilization or, in less aerobic environments, by increasing denitrification rates (Thomsen, Schjønning et al. 2003). For the first 30 to 40 days following manure application, no nitrification occurred followed by a period of exponential increase. A limit to nitrification was not reached by 180 days after incubation (Thomsen, Schjønning et al. 2003). Immediately after manure application, the low net nitrification may have occurred due to the assimilation of NO_3 by microorganisms after they had depleted the NH_4 stock. The NH_4 is assimilated preferentially over NO_3 (Mary, Recous et al. 1998). In the short term, soil microbes begin to assimilate more NO_3 when they had exhausted all of the NH_4 in their micro-environment, resulting in a depressed net nitrification (Mary, Recous et al. 1998). Since NH_4 is less mobile in soil solution than NO_3 (Mary, Recous et al. 1998)., this pattern may be particularly prevalent in newly amended soil, where NH_4 has not yet diffused completely from the amendment material to the soil.

Another study reported that when manure with high NH_4 content was applied to soil, net nitrification increased in a first-order pattern (Griffin, He et al. 2005). The increase then slowed 3 to 5 weeks after introduction to the soil, and reached a constant level around 7 weeks after introduction. The NH_4 disappearance rate in these systems matched the nitrification rate in the first weeks after manure application (Griffin, He et al. 2005).

Manure with low initial NH_4 concentrations (< 10 g/kg) had nitrification rates that either increased linearly, remained constant, or showed net immobilization (decreasing net nitrification over time) by microflora during a soil incubation of nearly 6 months. The NH_4 disappearance in these systems exceeded nitrification, indicating that NH_4 was being immobilized by the soil microflora before it could be nitrified.

These effects were enhanced as the fiber (NDF) content of the manure increased: net nitrification was quite low in fibrous manure (Griffin, He et al. 2005).

Composted manure amendments with high initial fiber and lignin contents increased the resistant and slow pools of soil organic carbon (SOC), and the N in these fractions was associated with lignin and with refractory humic substances produced during the decomposition of manure in soil (Fortuna, Harwood et al. 2003). Much of the N in manure was not readily available for mineralization by soil microbes. So, although the mineralization potential of manure N might be high, the retention time of the mineralizable, but not mineralized, N will be quite long (Fortuna, Harwood et al. 2003), resulting in a lower than expected amount of mineral N at any given time.

When immature, stockpiled manure is incorporated into soil, as opposed to being top-dressed as in no-till systems, smaller N losses via leaching and gaseous escape are observed (Chen, Cabrera et al. 2003). This effect is largely due to N immobilization by the soil microflora. In studies using cattle manure with a relatively high C:N of 28, decreased N losses were evident for three months after incorporation into soil (Chen, Cabrera et al. 2003). The N is tightly conserved in these systems, so any N released from microbial cell lysis is mineralized and immediately assimilated by growing cells. This rapid turnover prevents accumulation of mineral N into the pool of mineral N in the soil solution. The application of inorganic N fertilizer to soils in this state may result in a rapid assimilation of mineral N by the soil microbes. Large quantities of fertilizer would be required to exceed the immobilization potential of the microbes and to form a pool of mineral N. After a 3-month period of immobilization, the N loss pattern was similar to that of top-dressed manure (Chen, Cabrera et al. 2003). At this point, the organic carbon of the manure amendment was assimilated into microbial biomass, degraded to relatively stable humic substances with a short turnover, or lost via respiration or leaching. Microbial populations were in equilibrium at this stage (Chen, Cabrera et al. 2003).

When the C:N ratio is nearly halved to 15, a shift from net immobilization to net mineralization within only eight weeks was observed (Olayinka 2001). This behavior and the higher N content relative to the C content imply that N was plentiful and degradable by microbes and that the C substrates were fairly refractory. The microbes utilized the N and C compounds for growth until only the most refractory compounds remained, thereby creating an environment in which carbon was limiting. Net mineralization and the accumulation of a mineral N pool ensue.

Microbial biomass in manure-amended soils can be as large as 434 mg/kg of soil (Bittman, Forge et al. 2005). The large bacterial populations in manure-amended soil lead to a rapid immobilization of mineral N by microbes in the event of a sudden, large, labile or mineral N fertilization such as an urea application (Bittman, Forge et al. 2005). The bacteria quickly mineralize any labile, non-mineral N and then assimilate all mineral N. Bacterial population growth accelerates as the microorganisms synthesize new proteins and reproduce using labile carbon substrates from the manure for energy.

Microbial activity depends on water availability, so the inconsistencies in observed patterns of nitrification may be due to differences in soil water availability between experiments (Thomsen, Schjønning et al. 1999). Generalizations about nitrification patterns in amended soils, especially in the first few weeks after the addition of the manure, are difficult to make because water availability is highly variable. For modeling purposes, experimental measurements of net nitrification should be collected for each site of interest, to obtain the best estimates of nitrification for the model's target region(s).

Denitrification losses of nitrous oxide tend to be greater in clayey soils than in more sandy soils (Del Grosso, Parton et al. 2006). Denitrification takes place under anaerobic conditions. Water-filled pores in soil are prime sites for the anaerobic denitrification process. Clay soils are usually more poorly drained than sandy soils and so contain more water-filled pores than do sandy soils (Rochette, Angers et al. 2008). Denitrification is therefore often favored in clay soils.

Manure C:N does not adequately predict manure N dynamics in soil: Although the contributions of manure to soil N and organic matter content are recognized, often only total elemental compositions, such as total N or total C, are measured and reported. Measurement of the total N content of manure does not reflect the proportions of mineral N and organic N (fiber-bound), which have very different availabilities to plants. Nor does it represent the rate at which the organic N is being mineralized and then nitrified to more plant-available forms.

Predictions of the behavior of manure in soil can be made based upon manure and soil C:N ratios, but the forms of organic carbon must be known in order to make accurate predictions. The observation of N immobilization in manure-amended soils has resulted in the use of manure C:N, fiber:N, C:NH_4, and other ratios to evaluate the potential plant-available N content of manure (Griffin, He et al. 2005). Because of the interactions between the different N fractions and the different carbon fractions, ratios that include specific descriptions of the C and N fractions better predict plant-available N than the simple C:N ratio.

Manure effects on soil pH: When immature manure amendments are applied to soil, the nitrification-suppressing effects of microbial N immobilization result in an increase in soil pH (Olayinka 2001). Nitrification of NH_4 cations involves the release of acidic protons into the soil solution. As nitrification rates decrease, the proton release rates decrease in turn, and NH_4 cations accumulate in the soil, causing the soil pH to increase. The ability of manure to increase soil pH can counteract the acidification of soils by inorganic N fertilizers, that contain much mineral N that is nitrified rapidly in soil (Olayinka 2001), resulting in high rates of proton release.

Summary

This review has demonstrated the importance of manure as an organic soil amendment, especially in systems with severe soil degradation and limited funds for purchasing commercial fertilizers such as small farms in Kenya. While the benefits of manure amendments are recognized, manure is a complex material which should be managed carefully during the animal, storage, and soil application stages. The review also described cattle housing and feeding patterns on smallholder Kenyan farms. The background provided by this review paves the way for the two main areas of concentration of the research portion of the dissertation:

1) Do the manure storage techniques used on small farms in Kenya produce a soil amendment with a maximized mineral N content? Manure storage techniques currently in use on small farms in Kenya are expected to produce manure with sub-maximal levels of mineral N. The refractory, fiber- and lignin-bound N compounds not degraded during ruminant digestion or storage, or created in storage decomposition processes are expected to persist in soil beyond a single growing season.

2) What is the extent of the variability of diets fed to cattle on small Kenyan farms using the cut-and-carry system and what are the implications of this variability? It is hypothesized that the variability of cut-and-carry cattle diets is quite large and has an unfavorable effect on dairy cattle production.

Using this literature review as a foundation, the remainder of the dissertation seeks to evaluate these hypotheses.

REFERENCES

Agenas, S., E. Burstedt, et al. (2003). "Effects of feeding intensity during the dry period. 1. Feed intake, body weight, and milk production." Journal of Dairy Science 86: 870-882.

Allen, M. S. (2000). "Effects of diet on short-term regulation of feed intake by lactating dairy cattle." Journal of Dairy Science 83: 1598-1624.

Ambler, C. H. (1988). Kenyan Communities in the Age of Imperialism. New Haven, Yale University Press.

Aoyama, M., D. A. Angers, et al. (1999). "Particulate and mineral-associated organic matter in water-stable aggregates as affected by mineral fertilizer and manure applications." Canadian Journal of Soil Science 79: 295–302.

Bastyr, S. B. and W. J. Powers (2001). Effects of Manure Storage Time and Filling Scheme on Odor and Headspace Analysis Using Simulated Manure Storage Pits. Management/Economics, Swine Reports, Iowa Pork Industry Center, Ames, IA, Iowa State University.

Bationo, A., J. Kimetu, et al. (2003). "The African Network for Soil Biology and Fertility: New Challenges and Opportunities." Retrieved January 10, 2009, from http://www.ciat.cgiar.org/tsbf_institute/pdf/AfNet_challenges_opportunities.pdf.

Bethlenfalvay, G. J., I. C. Cantrell, et al. (1999). "Relationships between soil aggregation and mycorrhizae as influenced by soil biota and nitrogen." Biology and Fertility of Soils 28: 356–363.

Bittman, S., T. A. Forge, et al. (2005). "Responses of the bacterial and fungal biomass in a grassland soil to multi-year applications of dairy manure slurry and fertilizer." Soil Biology and Biochemistry 37: 613-623.

Borton, L. R. and C. A. Rotz (1995). "Simulation to evaluate dairy manure systems." Applied Engineering in Agriculture 11(2): 301-310.

Bradford, M. A., G. M. Tordoff, et al. (2002). "Microbiota, fauna, and mesh size interactions in litter decomposition." Oikos 99: 317–323.

Bussink, D. W. (1992). "Ammonia volatilization from grassland receiving nitrogen fertilizer and rotationally grazed by dairy cattle." Fertilizer Research 33: 257-265.

Bussink, D. W. and O. Oenema (1998). "Ammonia volatilization from dairy farming systems in temperate areas: a review." Nutrient Cycling in Agroecosystems 51: 19-33.

Cassman, K. G. and D. N. Munns (1980). "Nitrogen mineralization as affected by soil moisture, temperature, and depth." Soil Science Society of America Journal 44: 1233-1237.

Cegarra, J., A. Vazquez, et al. (1987). Changes undergone by some characteristics of organic wastes during the composting process. Compost: Production, Quality and Use. M. P. F. M. De Bertoldi, P. L'Hermite and F. Zucconi, eds. London, Elsevier Applied Science: 776-780.

Chen, X., M. L. Cabrera, et al. (2003). "Long-term decomposition of organic materials with different carbon/nitrogen ratios." Communications in Soil Science and Plant Analysis 34(1-2): 41-54.

Cleaver, K. M. and G. A. Schreiber (1992). Reversing the spiral. The population, agriculture and environment nexus in sub-Saharan Africa. Washington, D.C., World Bank, Africa Region.

Conelly, W. T. and M. Chaiken, S. (2000). "Intensive farming, agro-diversity, and food security under conditions of extreme population pressure in western Kenya." Human Ecology 28(1): 19-51.

Conrad, H. R., A. D. Pratt, et al. (1964). "Regulation of feed intake in dairy cows. I. Change in importance of physical and physiological factors with increasing digestibility." Journal of Dairy Science 47(1): 54-62.

Cortet, J., D. Gillon, et al. (2002). "Effects of pesticides on organic matter recycling and microarthropods in a maize field: use and discussion of the litterbag methodology." European Journal of Soil Biology 38: 261-265.

Couteaûx, M.-M., M. Mousseau, et al. (1991). "Increased atmospheric CO_2 and litter quality: decomposition of sweet chestnut leaf litter with animal food webs of different complexities." Oikos 61: 54-64.

Crossley, D. A. and M. P. Hoglund (1962). "A litter-bag method for the study of microarthropods inhabiting leaf litter." Ecology 43(3): 571-573.

Del Grosso, S. J., W. J. Parton, et al. (2006). "DAYCENT national-scale simulations of nitrous oxide emissions from cropped soils in the United States." Journal of Environmental Quality 35: 1451-1460.

Alice N Pell

DAIRY CATTLE FEEDING AND MANURE MANAGEMENT ON SMALLHOLDER FARMS IN KENYA

Helen Ann Markewich, Ph. D.

Cornell University 2009

The problem of declining soil fertility poses challenges to crop production on small-holder farms in the Kenyan highlands. Careful management of nutrients on resource-poor farms can support crop growth beyond subsistence needs with little or no cash expenditures by the farmer. Whether common manure management methods on smallholder Kenyan farms conserve nitrogen, a nutrient important for plant growth, was evaluated in two experiments. In the first experiment, the effects of shade and containment structure on the nitrogen composition of manure were tested in simulated storage units. The second experiment tested the effects of urine amendment on manure nitrogen composition. Both experiments tested manure age and cattle nutrition for their influence on manure nitrogen composition. Only cattle diet affected manure composition: better-fed animals produced manure with more mineralizable nitrogen available for plant uptake within one season. Up to 12% of the mineral nitrogen in manure was lost after 30 days in storage. To conserve mineral nitrogen, manure should be stored for no more than three weeks before it is applied to soil. Nutritionally adequate diets improved manure quality in terms of mineral nitrogen. Efforts to improve cattle nutrition on small-holder farms, such as supplementing diets with high-protein forages or supplements and developing models to predict production based on nutrition, are hindered by the large dietary variability in cut-and-carry systems. In a third experiment, feeding patterns on twelve small Kenyan farms were

monitored. Large variations in daily feed offered and intake were observed due to forage composition, preferential feeding of high-quality feeds to adult cows, and feeding animals in groups. Specialty, non-staple forages were offered to cattle no more than 6% of the time in any season. Steps may be taken to reduce the variation in intake, such as measuring feeds offered and feeding animals individually. Simulations using the Cornell Net Carbohydrate and Protein System (CNCPS) suggest that concentrate feeds elevate the energy and protein status of cows most significantly in early lactation and are less important to cows in late lactation. Milk production may be supported by offering concentrate supplements to cows in early lactation only.

Dewes, T. (1995). Nitrogen losses from manure heaps. Nitrogen leaching in ecological agriculture: Selected papers from an International Workshop, Royal Veterinary and Agricultural University, Copenhagen, Denmark, October 1993, AB Academic Publishers.

Eghball, B. (2000). "Nitrogen mineralization from field-applied beef cattle feedlot manure or compost." Soil Science Society of America Journal 64: 2024-2030.

Eghball, B. and J. F. Power (1999). "Phosphorus and nitrogen-based manure and compost application: corn production and soil phosphorus." Soil Science Society of America Journal 63: 895-901.

Eghball, B., B. J. Wienhold, et al. (2002). "Mineralization of manure nutrients." Journal of Soil and Water Conservation 57(6): 470-473.

Esse, P. C., A. Bueckert, et al. (2001). "Decomposition of and nutrient release from ruminant manure on acid sandy soils in the Sahelian zone of Niger, West Africa." Agriculture, Ecosystems and Environment 83: 55-63.

Fortuna, A., R. Harwood, et al. (2003). "Optimizing nutrient availability and potential carbon sequestration in an agroecosystem." Soil Biology and Biochemistry 35: 1005–1013.

Friggens, N. C., G. C. Emmans, et al. (1998). "Feed intake relative to stage of lactation for dairy cows consuming total mixed diets with a high or low ratio of concentrate to forage." Journal of Dairy Science 81: 2228-2239.

Griffin, T. S., Z. He, et al. (2005). "Manure composition affects net transformation of nitrogen from dairy manures." Plant and Soil 273: 29–38.

Havlin, J. L., J. D. Beaton, et al. (2005). Soil Fertility and Fertilizers: An Introduction to Nutrient Management. Upper Saddle River, New Jersey, Pearson Education, Inc.

Horwarth, W. (2007). Carbon cycling and formation of soil organic matter. Soil Microbiology, Ecology, and Biochemistry. P. E. A. Amsterdam, Academic Press: 303-339.

Ingvartsen, K. L. and J. B. Andersen (2000). "Integration of metabolism and intake regulation: A review focusing on periparturient animals." Journal of Dairy Science 83: 1573-1597.

Jama, B., R. A. Swinkels, et al. (1997). "Agronomic and economic evaluation of organic and inorganic sources of phosphorus in western Kenya." Agronomy Journal 89: 597-604.

Jarrige, R., C. Demarquilly, et al. (1986). "The INRA "Fill Unit" system for predicting the voluntary intake of forage-based diets in ruminants: A Review." Journal of Animal Science 63: 1737-1758.

Kamoni, P. T., P. T. Gicheru, et al. (2007). "Predicted soil organic carbon stocks and changes in Kenya between 1990 and 2030. In: Milne, E., Powlson, D.S., Cerri, C.E.P. (Eds.), Soil Carbon Stocks at Regional Scales." Agriculture, Ecosystems and Environment 122: 105-113.

Karanja, N. K., E. M. Gichangi, et al. (2005). "Simulation study to assess the potential of selected agro-organic wastes for ability to reduce N volatilization from cow manure." Tropical and Subtropical Agroecosystems 5: 25-31.

Klausner, S. D., V. R. Kanneganti, et al. (1994). "An approach for estimating a decay series for organic nitrogen in animal manure." Agronomy Journal 86: 897-903.

Lee, D. R., C. B. Barrett, et al. (2006). "Policy, technology, and management strategies for achieving sustainable agricultural intensification." Agricultural Economics 24: 123-127.

Lekasi, J. K., J. C. Tanner, et al. (2001). Manure Management in the Kenya Highlands: Practices and Potential, 2nd Edition. High Potential Production System Portfolio of the Natural Resources Systems Programme Renewable Natural Resources Knowledge Strategy Department for International Development. Ryton-on-Dunsmore, The Henry Doubleday Research Association (HDRA): 32.

Lekasi, J. K., J. C. Tanner, et al. (2003). "Cattle manure quality in Maragua District, Central Kenya: effect of management practices and development of simple methods of assessment." Agriculture, Ecosystems and Environment 94: 289-298.

Marenya, P. P. (2008). Three essays on the effect of ex-ante soil fertility on smallholder fertilizer use behavior. Cornell University, Ithaca, New York. Ph.D. Dissertation.

Martins, O. and T. Dewes (1992). "Loss of nitrogenous compounds during composting of animal wastes." Bioresource Technology 42: 103-111.

Mary, B., S. Recous, et al. (1998). "A model for calculating nitrogen fluxes in soil using ^{15}N tracing." Soil Biology & Biochemistry 30: 1963–1979.

Mathur, S. P. (1991). Composting Processes. Bioconversion of Waste Materials to Industrial Products. e. A. M. Martin. London, Elsevier: 147-186.

Mathur, S. P., H. Dinel, et al. (1993). "Determination of compost biomaturity II. Optical density of water extracts of composts as a reflection of their maturity." Biological Agriculture and Horticulture 10: 87-108.

Mathur, S. P., G. Owen, et al. (1993). "Determination of compost biomaturity I. Literature Review." Biological Agriculture and Horticulture(10): 65-85.

Milne, E., K. Paustian, et al. (2007). "An increased understanding of soil organic carbon stocks and changes in non-temperate areas: National and global implications." Agriculture, Ecosystems and Environment 122: 125-136.

Misselbrook, T. H., J. M. Powell, et al. (2005). "Dietary manipulation in dairy cattle: laboratory experiments to assess the influence on ammonia emissions." Journal of Dairy Science 88(5): 1765-1777.

Mortimore, M. (1998). Roots in the African Dust: Sustaining the Sub-Saharan Drylands. Cambridge, Cambridge University Press.

Muck, R. E. and B. K. Richards (1983). "Losses of manurial nitrogen in free-stall barns." Agricultural Wastes 7(2): 65-79.

Muck, R. E. and T. S. Steenhuis (1980). N losses in free stall dairy barns. Livestock Waste: A Renewable Resource. Proceedings 4th International Symposium on Livestock Wastes, St. Joseph, MI, American Association of Agricultural Engineers.

Muck, R. E. and T. S. Steenhuis (1981). Nitrogen losses in free stall dairy barns. Livestock Waste: A Renewable Resource. Proceedings 4th International Symposium on Livestock Wastes, St. Joseph, MI, American Society of Agricultural Engineers.

Muck, R. E. and T. S. Steenhuis (1982). "Nitrogen losses from manure storages." Agricultural Wastes 4: 41–54.

Mugwira, L. M., J. Nyamangara, et al. (2002). "Effects of manure and fertilizer on maize at a research station and in a smallholder (peasant) area of Zimbabwe." Communications in Soil Science and Plant Analysis 33(3 & 4): 379-402.

Murwira, H. K., M. J. Swift, et al. (1995). Animal-soil interactions: Manure as a key resource in sustainable agriculture. Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of sub-Saharan Africa. Vol. II: Technical Papers. Proceedings of an international conference held in Addis Ababa, Ethiopia, 22-26 November 1993. J. M. Powell, S. Fernandez-Rivera, T. O. Williams and C. Renard. Addis Ababa, International Livestock Centre for Africa: 131-148.

National Research Council (2001). Nutrient Requirements of Dairy Cattle, Seventh Revised Edition. C. o. A. N. Subcommittee on Dairy Cattle Nutrition, Board on Agriculture and Natural Resources. Washington D.C., National Academy Press.

Nherera, F. V. (2006). Predicting energy and protein supply and milk production of dairy cows consuming high forage rations in the eastern highlands of Kenya. Cornell University, Ithaca, New York. Ph.D. Dissertation.

Nzuma, J. K. and H. K. Murwira (2000). Improving the management of manure in Zimbabwe. Managing Africa's Soils no. 15. London, UK, Drylands Programme, International Institute for Environment and Development: 608.

Olayinka, A. (2001). "Effect of co-applied cowdung and inorganic nitrogen on microbial respiration in soil under laboratory conditions." Communications in Soil Science and Plant Analysis 32(19-20): 3229–3242.

Onduru, D. D. and C. C. Du Preez (2007). "Ecological and agro-economic study of small farms in sub-Saharan Africa." Agronomy for Sustainable Development 27: 197-208.

Overcash, M. R., F. J. Humenik, et al. (1983). Livestock waste management. Boca Raton, CRC Press.

Ovuka, M. (2000). "More people, more erosion? Land use, soil erosion and soil productivity in Murang'a District, Kenya." Land Degradation & Development(11): 111-124.

Paul, J. W. and E. G. Beauchamp (1989). "Effect of carbon constituents in manure on denitrification in soil." Canadian Journal of Soil Science 69: 49–61.

Peacock, A. D., M. D. Mullen, et al. (2001). "Soil microbial community responses to dairy manure or ammonium nitrate applications." Soil Biology and Biochemistry 33: 1011–1019.

Rochette, P., D. A. Angers, et al. (2008). "N2O fluxes in soils of contrasting textures fertilized with liquid and solid dairy cattle manures." Canadian Journal of Soil 88: 175-187.

Salamanca, E. F., N. Kaneko, et al. (1998). "Effects of leaf litter mixtures on the decomposition of *Quercus serrata* and *Pinus densiflora* using field and laboratory microcosm methods." Ecological Engineering 10: 53-73.

Sørensen, P. (1998). "Carbon mineralization, nitrogen immobilization and pH change in soil after adding volatile fatty acids." European Journal of Soil Science 49: 457–462.

Spear, T. (1981). Kenya's Past: An Introduction to Historical Method in Africa. London, Longman Group Ltd.

Subair, S., J. W. Fyles, et al. (1999). "Ammonia volatilization from liquid hog manure amended with paper products in the laboratory." Journal of Environmental Quality 28: 202 - 207.

Tamminga, S. (1992). "Nutrition management of dairy cows as a contribution to pollution control." Journal of Dairy Science 75: 345–357.

Thomsen, I. K., P. Schjønning, et al. (1999). "Turnover of organic matter in differently textured soils. II. Microbial activity as influenced by soil water regimes." Geoderma 89: 199–218.

Thomsen, I. K., P. Schjønning, et al. (2003). "C and N turnover in structurally intact soils of different texture." Soil Biology and Biochemistry 35: 765-774.

Tisdall, J. M., Oades, J.M. (1982). "Organic matter and water-stable aggregates in soils." Journal of Soil Science 33: 141–163.

Ulén, B. (1993). "Losses of nutrients through leaching and surface runoff from manure-containing composts." Biological Agriculture and Horticulture 10(29-37).

Unc, A. and M. J. Goss (2004). "Transport of bacteria from manure and protection of water resources." Applied Soil Ecology 25: 1–18.

Van der Hoek, K. W. and J. Oosthoek (1985). Composting: odour emission and odour control by biofiltration. Composting of Agricultural and Other Wastes. e. J. K. R. Gasser. London, Elsevier Applied Science: 271-281.

Van Soest, P. J. (1994). Nutritional Ecology of the Ruminant, 2nd ed. Ithaca, Cornell University Press.

Vigil, M. F., B. Eghball, et al. (2002). "Accounting for seasonal nitrogen mineralization: An overview." Journal of Soil and Water Conservation 57(6): 464-469.

von Fragstein, P. (1995). Manuring, manuring strategies, catch crops and N-fixation. Nitrogen leaching in ecological agriculture: Selected papers from an International Workshop, Royal Veterinary and Agricultural University, Copenhagen, Denmark, October 1993, AB Academic Publishers.

Vossbrinck, C. R., D. C. Coleman, et al. (1979). "Abiotic and biotic factors in litter decomposition in a semiarid grassland." Ecology 60(2): 265-271.

Zingore, S., H. K. Murwira, et al. (2007). "Soil type, management history and current resource allocation: Three dimensions regulating variability in crop productivity on African smallholder farms." Field Crops Research 101: 296-305.

CHAPTER 2

EFFECTS OF STORAGE METHODS ON MANURE SYSTEMS AND MANURE DECOMPOSITION IN SOIL IN SMALL-SCALE KENYAN SYSTEMS

Abstract

Using cattle manure as a soil amendment can provide considerable amounts of mineral N to soil if managed correctly. Manure management techniques vary among smallholder Kenyan farms, yet the quality of manure produced by each method has not been assessed. This study was designed to examine the effects of storage method on the N content and N fractionation of the manure. The management techniques tested were pit vs. pile containment, shade vs. no shade, and daily vs. single addition of manure to the storage system. Manure samples from two dairy farms with different levels of animal management and diet quality were stored for 30 days in experiments with randomized complete block designs. Three replicates of each of 8 treatments were sampled every 6 days. The N composition of the manure was monitored during the study. Manure aged 30 days was buried in soil in large- and small-mesh litterbags. The disappearance of organic-N was monitored over 4 months at 7 intervals over 112 days for each of the 36 storage replicates. Time in storage ($P < 0.03$) and farm of origin ($P < 0.0001$) were the only variables to influence the organic N composition of the stored manure. Manure origin ($P < 0.04$) and time in storage ($P < 0.0001$) were also the only variables to affect the mineral N composition of the stored manure. Manure N from the farm with better management (Medium quality manure) disappeared more quickly than N in manure from the less well-managed farm (Low quality manure): 7.0 % more organic N remained intact in the Low quality manure after 112 days in soil, compared to the Medium quality manure. More N may be

available for uptake by plants during one growing season if manure from better-fed cattle is used as a soil amendment.

Introduction

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

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

The objective of this study was to examine the compositional changes in cattle manure induced by manure storage method, with an emphasis on nitrogenous compounds. It was hypothesized that pits produce manure with more NH_4-N and less refractory N than piles because the exposed surface area of manure in pits is less than that of manure in piles, resulting in a smaller area from which ammonia may volatilize. Another hypothesis was that shaded storage units produce manure with more NH_4-N and less refractory N than units exposed to full sunlight because manure exposed to sunlight is warmer than shaded manure. Ammonia volatilization increases with warmer temperatures. A third hypothesis stated that units to which fresh manure is added daily produce manure with more NH_4-N and less refractory N than units with manure of a single age. Fresh manure contains more readily degradable N and C compounds than older stockpiled manure and fresh manure degrades more quickly in soil than older manure (Atallah, Andreux et al. 1995). The fourth hypothesis was that large N losses from stored manure occur within the first month of storage. Losses of 12.5 % of the initial manure N content were observed in beef cattle manure stockpiled for 42 days (Luebbe, Erickson et al. 2008). The fifth hypothesis stated that when manure is applied to the soil, manure NH_4-N disappears in the first 2 weeks. Ammonium-N in manured soil fell to trace levels only 1 to 2 weeks after application (Atallah, Andreux et al. 1995; Calderon, McCarty et al. 2004). The disappearance of NH_4-N results from immobilization of the NH_4-N except in manures with a C:N of 8.5 or less (Atallah, Andreux et al. 1995). Denitrification may account for some of the NH_4-N disappearance, since it results in the loss of approximately 5 % of manure N after soil application (Calderon, McCarty et al. 2004). Ammonium-N in the soil solution may be nitrified and become available to plants if the manure application is synchronized with plant nutrient uptake. Nitrification in manured soil produced a net increase in soil nitrate levels during 6 weeks of incubation (Calderon, McCarty et al. 2004). Finally, it was hypothesized that refractory manure N compounds persist beyond three months in soil. An 80-day incubation of manure resulted in C and N mineralization rates that slowed towards the end of the incubation as the pool of readily degradable compounds was depleted by soil microbes, leaving the more slowly degradable cellulose and lignin in the soil (Atallah, Andreux et al. 1995).

Materials and Methods

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

The larger dairy farm had a herd of 300 Holstein-Friesian cattle with a milking herd of 90 cows. The cows grazed Rhodes grass (*Chloris gayana*) pasture for half of the day. For the remainder of the day, the herd was confined and fed a balanced ration of corn silage, Napier grass (*Pennisetum purpureum*), and a concentrate mix (.Table. 2.1.). Manure from the larger farm will be referred to as "Medium quality" manure from this point.

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

Table 2.1 Formulation of concentrate mix fed to the dairy herd producing Medium quality manure.

Ingredient	Mass (kg)	% of total mass
Ground whole maize ears (cobs + kernels)	75	30
Maize germ	29	11.6
Corn gluten feed	20	8
Prairie meal	11	4.4
Wheat bran	45	18
Cottonseed cake	60	24
Stock feed lime	7	2.8
Yeast	0.25	0.1
Salt	1.5	0.6
Dairy Premix (energy supplement)	0.25	0.1
Super Maclik (mineral supplement)	1	0.4
Total	**250**	**100**

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

Manure from the milking herds of each farm was collected from the building where the cattle were confined before milking. The differences in cattle diet resulted in differences in the initial composition of the manure used in the study. The Medium quality manure had a smaller total organic N content than the Low quality manure, but the Low quality manure had a larger NDIN fraction (Table 2.2). This implies that the

Low quality manure had more N bound in slowly degradable compounds than the Medium quality manure.

Table 2.2 Initial composition of manure used in the storage experiment.

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

Two experiments with randomized complete block designs with repeated measures were conducted (Table 2.3). One experiment tested the effects of containment method, manure quality, and application rate, while the other experiment tested the effects of containment method and shade. In both experiments, 3 replicates of each treatment were incubated in each plot. "Medium quality" and "Low quality" manure units received manure from the larger and smaller dairy herds, respectively. Manure units denoted "One-time" received a single application of 30 kg fresh weight of manure at the beginning of the experiment. In the "Daily" addition treatment, 1.3 kg of manure (fresh weight) were added daily over 30 days. The manure "Pits" were holes with dimensions of 0.76 m x 0.76 m x 0.46 m. Manure was added to the center of the pits. In the "Pile" manure units, manure was added to the center of unbroken ground of each plot. The effects of pit or pile, manure quality, and application type were tested in one randomized experiment.

Treatments for the shading experiment were randomly assigned in a separate randomized experiment. "Shaded" treatments received 50% shade from greenhouse shading material suspended above the manure. "Unshaded" were not shaded with any material (Table 2.3).

Table 2.3 Treatments in the manure storage experiments testing the effects of manure quality (Medium quality vs. Low quality), frequency of application (Daily vs. One-time), exposure to sunlight (Unshaded vs. Shaded) and containment method (Piles vs. Pits).

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

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

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

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

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

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

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

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

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

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

Results

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

Manure storage experiment: Results of the mixed model analyses appear in Tables 2.4 – 2.5. Neither the application method (daily, one-time), the containment method (pit, pile), nor the presence of shade affected the manure NH_4-N, organic N, and fiber-bound N content at any time ($\alpha = 0.01$). The individual manure unit had a significant effect on the DM, total organic N, ADIN, and NDIN content of the manure in the manure quality experiment. The individual manure unit accounted for 4.3 % of the variation in total organic N, 41.7 % of the variation in ADIN, and 16.0 % of the variation in NDIN. The NH_4-N data were not affected by the individual manure unit. The individual manure unit had no effect on the variance of any of the results in the shading experiment.

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

Table 2.4. ANOVA results for NH_4-N content (mg NH_4-N / kg manure, DM basis), dry matter content (DM, % of fresh weight), organic matter content (OM, % of DM), N content (N, % of OM), acid-detergent insoluble N (ADIN, % of OM), and neutral-detergent insoluble N (NDIN, % of OM) of manure in storage. Fixed effects are the manure quality (Medium quality vs. Low quality), the manure application rate (one-time vs. daily application), the containment method (pit vs. pile), and the number of days the manure spent in storage (0, 6, 12, 18, 24, or 30 days). Terms for the interaction between fixed effects are denoted by fixed effects terms separated by an asterisk (*). DF represents the degrees of freedom of the test.

		P - value					
Effect	DF	NH_4-N (mg / kg manure)	DM (%)	OM (% of DM)	N (% of OM)	ADIN (% of OM)	NDIN (% of OM)
Medium quality vs. low quality manure [A]	1	0.0393	<0.0001	<0.0001	0.5707	0.6447	0.0013
One-time application vs. daily application [B]	1	0.151	0.1684	0.6552	0.1278	0.3396	0.005
Manure pit vs. pile [C]	1	0.6601	0.3737	0.5681	0.1515	0.2101	0.9462
Days in storage [D]	5	<0.0001	<0.0001	0.3681	<0.0001	<0.0001	<0.0001
A*B	1	0.6656	0.4435	0.9936	0.9564	0.455	0.3145
A*C	1	0.8427	0.2813	0.5653	0.1227	0.6419	0.1364
A*D	5	0.0007	0.0055	0.0683	0.0038	0.0577	<0.0001
B*C	1	0.3285	0.0792	0.8223	0.8935	0.153	0.207
B*D	5	0.0239	0.2666	0.9871	0.0222	0.1834	0.3867
C*D	5	0.1616	0.3466	0.9999	0.1332	0.8448	0.1659
A*B*C	1	0.1182	0.9278	0.9518	0.5837	0.5213	0.069
A*B*D	5	0.2252	0.6941	0.9052	0.1069	0.381	0.283
A*C*D	5	0.3669	0.9883	0.9801	0.5094	0.2519	0.7419
B*C*D	5	0.5333	0.0485	0.0521	0.9412	0.2875	0.7402
A*B*C*D	5	0.7021	0.2599	0.1236	0.4403	0.7407	0.9754

Table 2.5. ANOVA results for NH_4-N content (mg NH_4-N / kg manure, DM basis), dry matter content (DM, % of fresh weight), organic matter content (OM, % of DM), N content (N, % of OM), acid-detergent insoluble N (ADIN, % of OM), and neutral-detergent insoluble N (NDIN, % of OM) of manure in storage. Fixed effects are the presence or absence of shade, the containment method (pit vs. pile), and the number of days the manure spent in storage (0, 6, 12, 18, 24, or 30 days). Terms for the interaction between fixed effects are denoted by fixed effects terms separated by an asterisk (*). DF represents the degrees of freedom of the test.

		P - value					
Effect	DF	NH_4-N (mg / kg manure)	DM (%)	OM (% of DM)	N (% of OM)	ADIN (% of OM)	NDIN (% of OM)
Manure pit vs. pile [A]	1	0.272	0.4504	0.5169	0.9605	0.7491	0.6773
Days in storage [B]	5	<0.0001	0.2328	0.7993	<0.0001	0.0005	0.0784
Shade vs. no shade [C]	1	0.41	0.2808	0.1207	0.5075	0.3146	0.9307
A*B	5	0.5799	0.7581	0.5181	0.4739	0.94	0.7271
A*C	1	0.821	0.3236	0.7844	0.6459	0.675	0.1513
B*C	5	0.6256	0.7311	0.534	0.2111	0.2839	0.37
A*B*C	5	0.9928	0.2867	0.3267	0.349	0.6974	0.4165

NH_4-N per kg of manure (Figure 2.1). At the end of the 30-day experiment, the Medium quality manure contained 98 % of its initial NH_4-N while the Low quality manure retained only 60 % of its initial NH_4-N content.

The Medium quality manure had a smaller OM content than the Low quality manure at the beginning and end of the 30-day storage period (Figure 2.2). The Low quality manure contained 67.9 % OM (DM basis) at the start of the experiment and 64.3 % OM (DM basis) after 30 days of storage. The OM content of the Medium quality manure was 55.9 % (DM basis) at the start of the experiment and 50.8 % (DM basis) at the end of the 30-day storage period. Single-term exponential regression models of the OM dynamics appear in Figure 2.2. Double exponential regression of OM dynamics of manure in storage failed to converge.

The Low quality manure had greater initial concentrations of total organic N and NDIN than the Medium quality manure ($P < 0.01$, $P < 0.0008$). The Low quality manure contained 3.5 % N and (OM basis) and 1.8 % NDIN (OM basis) at the start of the storage experiment while the Medium quality manure contained 3.1 % organic N and (OM basis) and 1.4 % NDIN (OM basis) at the start of the storage experiment. The pool of the most refractory fiber-bound N, ADIN, was not significantly larger in the Low quality manure at the start of the experiment ($\alpha = 0.05$). The average ADIN content of manure from both treatments was 1.2 % (OM basis) at the start of the experiment. Manure ADIN content did differ between the treatments at the end of 30 days of storage ($P < 0.03$). The Medium quality manure contained 1.3 % ADIN (OM basis) and the Low quality manure contained 1.4 % ADIN (OM basis) after 30 days in storage. At the end of 30 days of storage, the Low quality manure contained more NDIN than the Medium quality manure (1.8 % vs. 1.4 % NDIN (OM basis), $P < 0.01$). There was no difference in organic N between the two treatments after 30 days of storage. The average organic N content of the manure of both treatments after 30 days

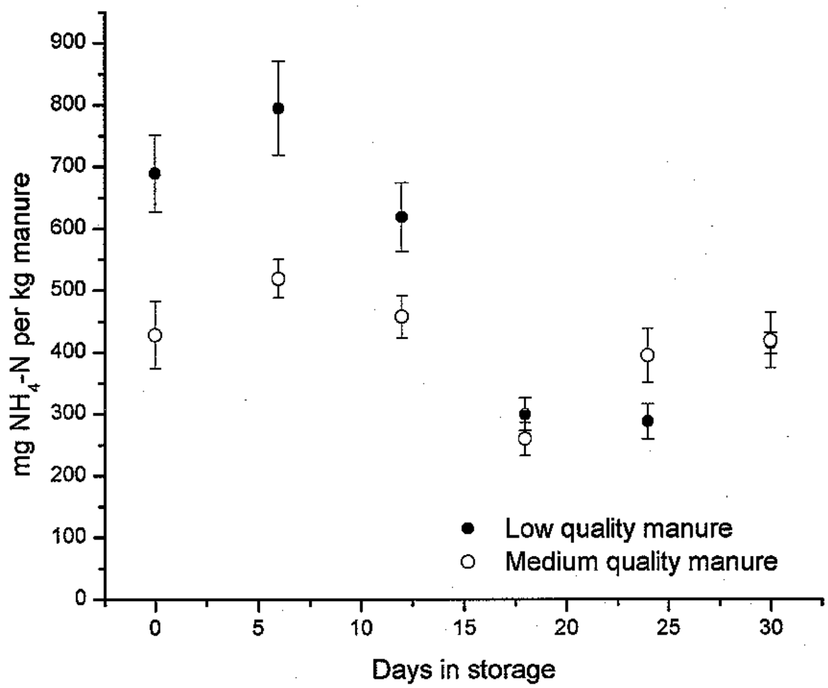


Figure 2.1. Ammonium-N dynamics in Medium quality manure and Low quality manure in storage. Error bars represent standard error of means. Discrete points represent the mean values of NH_4-N (mg per kg of manure) at each time point.

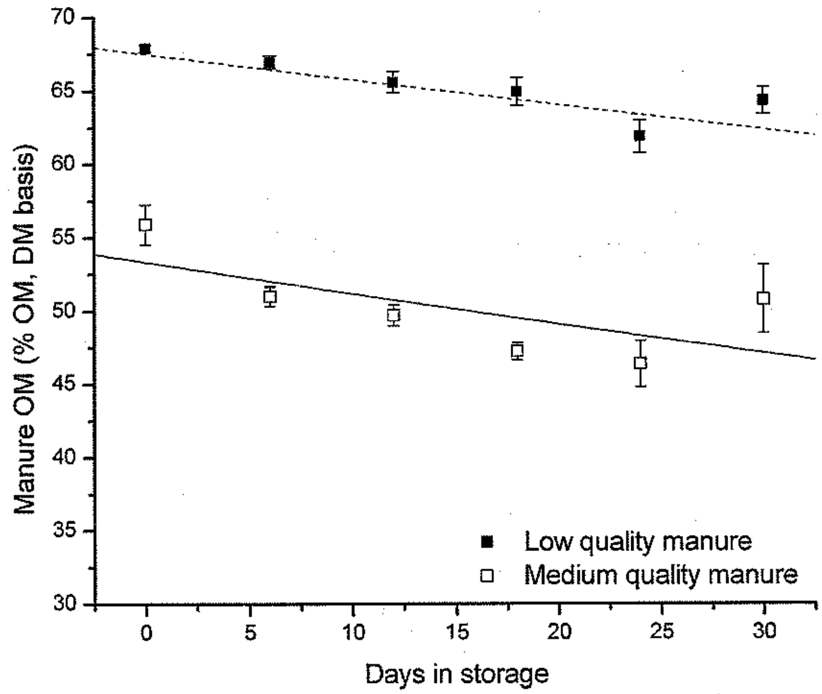


Figure 2.2. Total organic matter dynamics in manure in storage (% OM, DM basis). Error bars represent standard error of differences in means. Discrete points represent the mean values of % OM at each time point. Continuous lines represent the best fit regression equations for OM disappearance. Y represents the percentage of OM remaining in the litterbag sample. X represents the number of days in soil. The solid line (——) represents the best-fit regression line for Medium quality manure treatments. The dashed line (----) represents the best-fit regression line for Low quality manure treatments. Medium quality manure: $Y = 53.3358\ e^{-0.00414x}$, $R^2 = 0.990$. Low quality manure: $Y = 67.509\ e^{0.-00264x}$, $R^2 = 0.997$. The rate equations for OM dynamics between the manure sources did not differ at significance level $\alpha = 0.05$.

of storage was 4.0 % (OM basis). Exponential regression models of total N, NDIN, and ADIN dynamics with one exponential term appear in Figures 2.3a-c. Double exponential regression models to describe total N, NDIN, and ADIN dynamics of manure in storage failed to converge.

Litterbag experiment: Results of the mixed model analyses of the litterbag manure N composition data appear in Tables 2.6 – 2.7.

Considerably more organic matter was lost from the large-mesh litterbags than from the small-mesh litterbags over 112 days in soil ($P < 0.0001$), beginning from 8 days in soil ($P < 0.05$). From the large mesh litterbags, Medium quality manure lost 78.0 % of OM and Low quality manure lost 73.4 % of OM after 112 days in soil (DM basis). From Medium quality manure in small mesh litterbags 24.3 % of OM was lost after 112 days in soil (DM basis). From Low quality manure in small mesh litterbags, 31.1 % of OM was lost (DM basis). Figure 2.4 shows the kinetics of degradation from the activity of the soil organisms of microbial to mesofaunal size as they break down the manure. Exponential decay equations for OM disappearance appear in Figure 2.4. Organic matter decay was much more rapid in the large mesh litterbags, which allowed insects to break down the manure as well as microbes (Figure 2.4). Double exponential decay models of OM dynamics of manure in litterbags failed to converge.

The Low quality manure had lower concentrations of total organic N and fiber-bound N than the Medium quality manure at the start of the litterbag experiment: 3.9% organic N and 1.9 % NDIN (OM basis) vs. 4.1 % organic N and 2.1 % NDIN (OM basis), respectively. At the end of the experiment, the Low quality manure in small mesh litterbags contained 7.0 % more organic N and 14.0 % more NDIN than the Medium quality manure. The Low quality manure in the large mesh litterbags contained 3.1 % more organic N and 6.3 % more NDIN than the Medium quality manure after 112 days n soil. After 112 days in soil, the Medium quality manure in

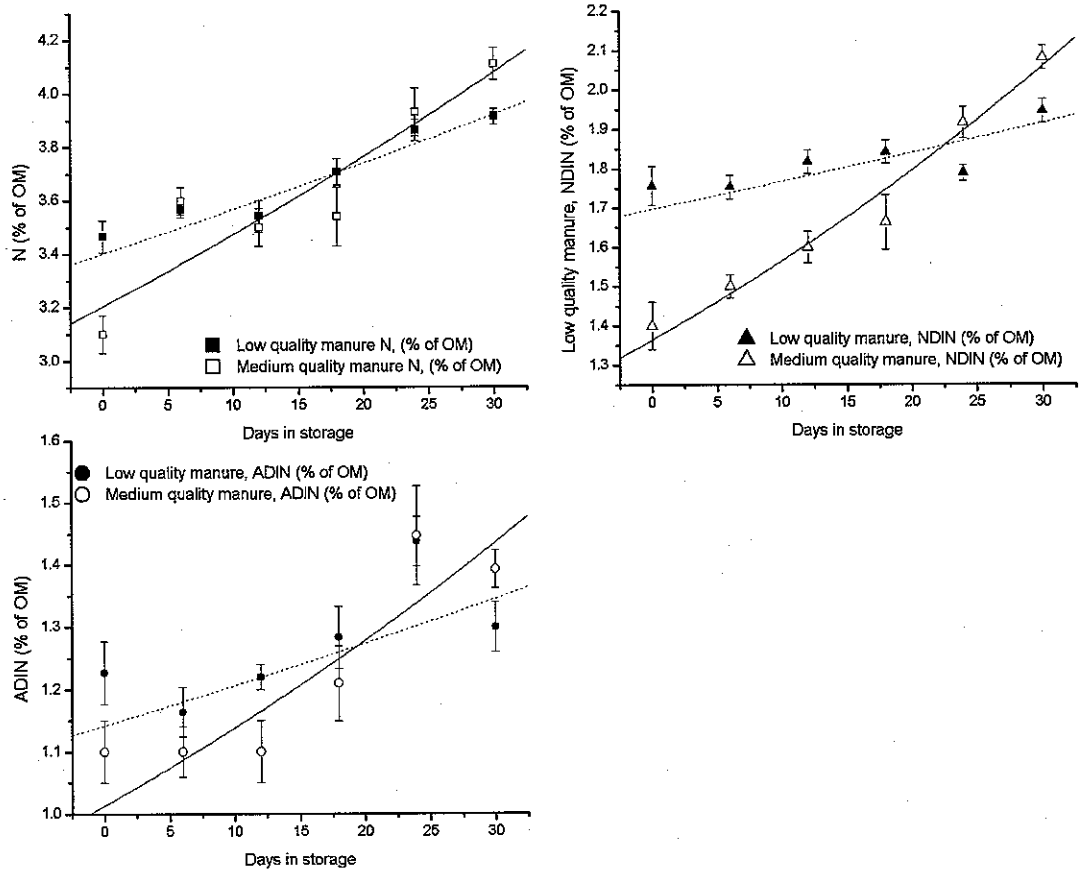


Figure 2.3. Total organic N, neutral detergent insoluble N (NDIN), and acid detergent insoluble N (ADIN) dynamics in manure in storage (DM basis). Error bars represent standard error of means. Continuous lines represent regression equations for organic N dynamics in manure during the dry season experiment. Solid lines (——) represent the best fit regression lines for Medium quality manure treatments. Dashed lines (----) represent the best fit regression lines for Low quality manure treatments. Y represents the amount of organic N, NDIN, or ADIN remaining in the manure (% of initial content, DM basis). Figure 2.3a (Top left). Total organic N dynamics (% N, DM basis). Medium quality manure: $Y = 3.2044\ e^{0.00804x}$, $R^2 = 0.994$. Low quality manure: $Y = 3.4021\ e^{0.00473x}$, $R^2 = 0.997$. The rate equations for organic N dynamics between the two manure sources differed ($P < 0.004$). Figure 2.3b (Top right). Neutral detergent insoluble N dynamics (% NDIN, DM basis). Medium quality manure: $Y = 1.3645\ e^{0.0137x}$, $R^2 = 0.991$. Low quality manure: $Y = 1.6971\ e^{0.00403x}$, $R^2 = 0.993$. The rate equations for organic N dynamics between the two manure sources differed ($P < 0.0001$). Figure 2.3c (Bottom left). Acid detergent insoluble N dynamics (% ADIN, DM basis). Medium quality manure: $Y = 1.0135\ e^{0.0116x}$, $R^2 = 0.977$. Low quality manure: $Y = 1.1419\ e^{0.00546x}$, $R^2 = 0.980$. The rate equations for ADIN dynamics between the manure sources differed ($P < 0.02$).

Table 2.6. ANOVA results for NH_4-N content (mg NH_4-N / kg manure, DM basis), dry matter content (DM, % of fresh weight), organic matter content (OM, % of DM), N content (N, % of OM), acid-detergent insoluble N (ADIN, % of OM), and neutral-detergent insoluble N (NDIN, % of OM) of manure in litterbags buried in soil. Fixed effects are manure quality (Medium quality vs. Low quality), the manure storage application rate (one-time vs. daily application), the storage containment method (pit vs. pile), the mesh size of the litterbag (small mesh vs. large mesh), and the number of days the manure spent in soil (0, 6, 12, 18, 24, 30, 48, 78, or 112 days). Terms for the interaction between fixed effects are denoted by fixed effects terms separated by an asterisk (*). DF represents the degrees of freedom of the test.

		P - value				
Effect	DF	DM (%)	OM (% of DM)	N (% of OM)	ADIN (% of OM)	NDIN (% of OM)
Medium quality vs. low quality manure [A]	1	<0.0001	<0.0001	<0.0001	0.0822	<0.0001
One-time application vs. daily application [B]	1	0.9566	0.4488	0.4776	0.4712	0.0122
Manure pit vs. pile [C]	1	0.054	0.4474	0.5564	0.0592	0.4394
Days in soil [D]	7	<0.0001	<0.0001	0.0471	<0.0001	<0.0001
Small mesh vs. large mesh litterbag [E]	1	<0.0001	<0.0001	<0.0001	<0.0001	0.0023
A*B	1	0.3114	0.0005	0.0321	0.8072	0.7918
A*C	1	0.0573	0.5586	0.0722	0.0601	0.7522
A*D	7	0.0445	<0.0001	0.0881	0.115	0.003
A*E	1	0.0993	<0.0001	0.1471	0.5724	0.277
B*C	1	0.9722	0.2132	0.5616	0.2955	0.3387
B*D	7	0.9612	0.221	0.6639	0.8072	0.0895
B*E	1	0.5181	0.0219	0.4857	0.8856	0.4532
C*D	7	0.1187	0.5768	0.8559	0.3325	0.5722
C*E	1	0.9393	0.3364	0.1109	0.0756	0.03
D*E	7	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
A*B*C	1	0.2109	0.7945	0.5294	0.0974	0.5465
B*C*D	7	0.8187	0.7315	0.7892	0.5434	0.9546
C*D*E	7	0.9198	0.7727	0.6183	0.7717	0.4176
A*B*D	7	0.7212	0.3753	0.8259	0.541	0.2354
A*B*E	1	0.24	0.1101	0.1854	0.1029	0.4963
A*C*D	7	0.9322	0.9355	0.6975	0.4583	0.7804
A*D*E	7	0.0161	<0.0001	0.0173	0.3079	0.5893
A*C*E	1	0.603	0.4164	0.4495	0.4793	0.4591
B*C*E	1	0.3598	0.5563	0.9168	0.2549	0.7099
B*D*E	7	0.6594	0.7786	0.4693	0.2645	0.4361
A*B*C*D	7	0.518	0.9167	0.6845	0.3824	0.6009
A*B*C*E	1	0.0156	0.7559	0.1514	0.0618	0.6345
A*C*D*E	7	0.9601	0.814	0.3185	0.0309	0.2165
A*B*D*E	7	0.4778	0.9491	0.1487	0.1056	0.3044
B*C*D*E	7	0.947	0.9919	0.7173	0.8155	0.7624
A*B*C*D*E	7	0.4127	0.6646	0.201	0.7279	0.6466

Table 2.7. ANOVA results for NH_4-N content (mg NH_4-N / kg manure, DM basis), dry matter content (DM, % of fresh weight), organic matter content (OM, % of DM), N content (N, % of OM), acid-detergent insoluble N (ADIN, % of OM), and neutral-detergent insoluble N (NDIN, % of OM) of manure in litterbags buried in soil. Fixed effects are the presence or absence of shade, the containment method (pit vs. pile), the mesh size of the litterbag (small mesh vs. large mesh), and the number of days the manure spent in soil (0, 6, 12, 18, 24, 30, 48, 78, or 112 days). Terms for the interaction between fixed effects are denoted by fixed effects terms separated by an asterisk (*). DF represents the degrees of freedom of the test.

		P - value				
Effect	DF	DM (%)	OM (% of DM)	N (% of OM)	ADIN (% of OM)	NDIN (% of OM)
Manure pit vs. pile [A]	1	0.6679	0.9472	0.2005	0.2791	0.3789
Days in soil [B]	7	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Small mesh vs. large mesh litterbag [C]	1	<0.0001	<0.0001	<0.0001	<0.0001	0.0047
Shade vs. no shade [D]	1	0.0822	0.1891	0.1057	0.4142	0.9097
A*B	7	0.9411	0.8469	0.4129	0.9466	0.8439
A*C	1	0.3717	0.9488	0.8714	0.1815	0.3941
A*D	1	0.5567	0.7617	0.0111	0.4996	0.1212
B*C	7	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
B*D	7	0.1745	0.1809	0.2019	0.0002	0.4031
C*D	1	0.2356	0.0004	0.0171	0.3734	0.7841
A*B*C	7	0.7147	0.9787	0.9613	0.8316	0.9795
B*C*D	7	0.2032	0.573	0.0428	0.4243	0.9973
A*C*D	1	0.2244	0.8277	0.1332	0.7681	0.0839
A*B*D	7	0.743	0.9686	0.7271	0.1851	0.896
A*B*C*D	7	0.7461	0.6784	0.7368	0.5673	0.9044

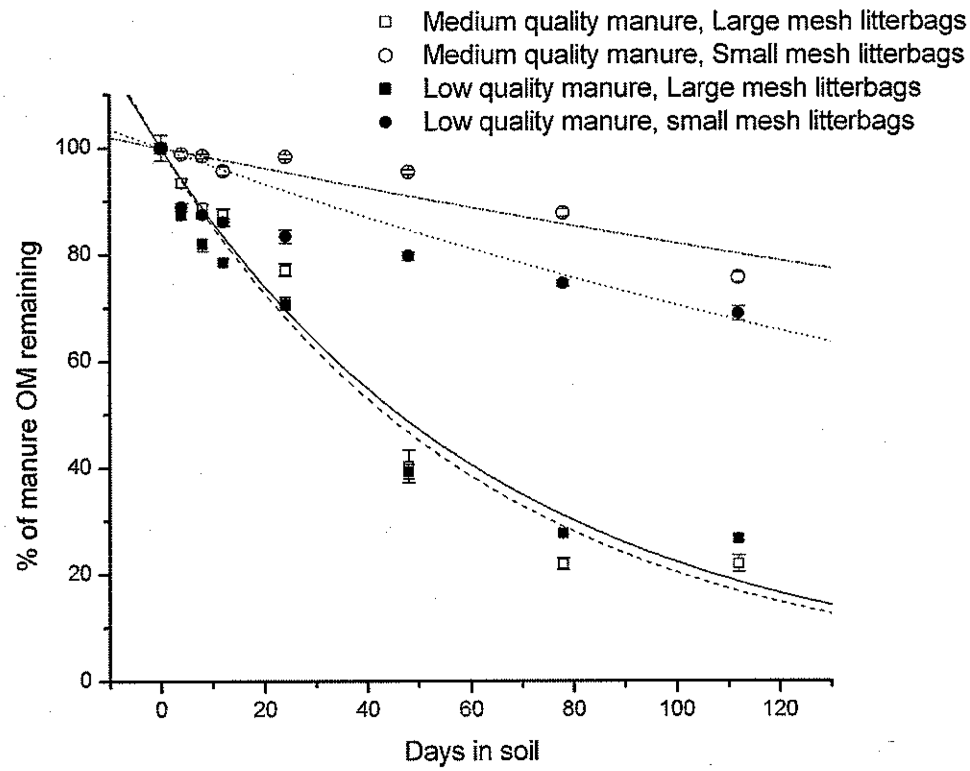


Figure 2.4. Fraction of Medium quality manure OM and Low quality manure OM remaining in litterbags buried in soil at each collection day (% of initial OM, DM basis). Error bars represent standard error of differences in means. Discrete points represent the mean values of % OM remaining at each time point. Continuous lines represent the best fit regression equations for OM disappearance. Y represents the percentage of OM remaining in the litterbag sample. The dashed line (----) represents the Low quality manure treatment in the large mesh litterbags. The solid line (——) represents the Medium quality manure treatment in the large mesh litterbags. The dotted line (••••) represents the Low quality manure treatment in the small mesh litterbags. The dot-dash line (-••-••) represents the Medium quality manure treatment in the small mesh litterbags. Solid lines represent Medium quality manure treatments. Medium quality manure, large mesh litterbags: $Y = 100\ e^{-0.0150x}$, $R^2 = 0.989$. Medium quality manure, small mesh litterbags: $Y = 100\ e^{-0.00349x}$, $R^2 = 0.994$. Low quality manure, large mesh litterbags: $Y = 100\ e^{-0.0159x}$, $R^2 = 0.980$. Low quality manure, small mesh litterbags: $Y = 100\ e^{-0.00198x}$, $R^2 = 0.998$.

large mesh litterbags contained 4.4 % organic N, 2.1 % NDIN, and 1.4 % ADIN (OM basis). Medium quality manure in small mesh litterbags contained 14.5 % organic N, 8.1 % NDIN, and 7.7 % ADIN (OM basis). After the 112-day period in soil, the Low quality manure in large mesh litterbags contained 4.9 % organic N, 1.9 % NDIN, and 1.4 % ADIN (OM basis). In small mesh litterbags, the Low quality manure contained 10.2 % organic N, 5.3 % NDIN, and 4.6 % ADIN (OM basis). The quality of the manure ($P < 0.0001$ for total organic N and NDIN) and the litterbag mesh size ($P < 0.0001$) were the only treatments to have a significant effect on total organic N, NDIN, or ADIN. The manure source had no effect on ADIN ($\alpha = 0.05$). The number of days in storage was also significant to the manure composition ($P < 0.0001$ for ADIN and NDIN, $P < 0.05$ for total organic N).

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

Discussion

Mineral N of manure in storage: Mineralization of the N in rapidly degradable organic fractions in manure may account for the increase in NH_4-N content seen during the first 6 days of storage: an increase of 15 % in the manure NH_4-N content (DM basis) in Low quality manure and an increase of 21 % in the NH_4-N content (DM basis) of the Medium quality manure (Figure 2.1). The NH_4-N concentration fell during the next 12 days as the N mineralization rate slowed because the pools of labile N compounds in the manure were depleted during the first 6 days. The NH_4-N losses via leaching, volatilization, and incorporation into microbial protein also contributed to the decrease in NH_4-N concentration. Overall, the data support the hypothesis that manure in storage loses large amounts of N, in the form of NH_4-N, when stored for 30 days. The application rate, the containment method, nor the shading had an effect on any component of manure N composition, so the hypotheses that a daily application rate, manure pits, and shaded systems produce manure with a larger NH_4-N than that of manure of a single age, manure piles, and manure exposed to full sunlight, are not supported.

Organic N of manure in storage: The concentrations of organic N, NDIN, and ADIN in the manure increased between 8 % to 50 % during the last 18 days in storage (Figure 2.2). These observed increases in N fractions may be due to a loss of manure mass (Martins and Dewes 1992). Decomposing material loses mass over time due to the mineralization of nutrients, and other degradation processes that cause structural disintegration (Dresbøll, Magid et al. 2006), especially of phenolics and lignin monomers that can be degraded within the 30 days of storage (Bidlack, Malone et al. 1992). When the bulk mass of the manure decreased more rapidly than the rate of loss of NH_4-N, the NH_4-N concentration increased. The failure to develop a two-term double exponential regression equation (Figure 2.2) suggests that the decay of both the more degradable organic compounds and the more refractory cellulose and lignin compounds do not greatly differ so as to require two exponential decay terms. The manure in this study came from cows fed low quality tropical forages. Poor quality forage diets lead to manure with more refractory cellulose and lignin compounds than rapidly degradable compounds (Vigil, Eghball et al. 2002). The fraction of OM capable of being degraded during 30 days of storage may have been too small to warrant its own term.

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

Where there are large soil mesofaunal populations present, a significant portion of manure applied as a soil amendment may be degraded and/or displaced by the soil insects (Seastedt 1984; Kaneko and Salamanca 1999; Esse, Bueckert et al. 2001). This is relevant for many areas in western Kenya with large indigenous populations of termites and ants in the soil. Termites have gut cellulases used to degrade the fibrous manure material. Termites and ants use the fibrous manure material in their mounds, so the activity of these insects may result in the relocation of manure from the soil as they transport it to their mounds (Potts and Hewitt 1973; Diamond 1998). When manure in litterbags was buried in the topsoil, the manure in the large mesh litterbags lost OM to a greater extent and more rapidly than that in the small mesh bags because of the activity of the soil mesofauna (Figure 2.4). Similar effects have been observed in other studies of African agroecosystems (Esse, Bueckert et al. 2001). These losses did not occur in the small mesh litterbags because the mesofauna could not pass through the smaller apertures. In addition, the large mesh apertures allowed for more contact between the manure and the soil. The larger apertures allowed for more manure degradation to occur since more sites are accessible for degradation (Seastedt 1984). Exponential regression was successful when only one term was used, suggesting that the fraction of refractory cellulose and lignin compounds in manure, originating from the poor quality forages in the cattle diets, was large. The pool of degradable compounds may have been too small for its degradation in soil to be described by a separate term in the exponential regression.

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

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

Conclusions

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

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

REFERENCES

Anderson, J. M. and J. S. I. Ingram, Eds. (1993). Tropical Soil Biology and Fertility: A Handbook of Methods. Wallingford, C•A•B International.

AOAC (2000). 954.01 Protein (Crude) in Animal Feed, Forage (Plant Tissue), Grain, and Oilseeds. Official Methods of Analysis of the Association of Official Analytical Chemists. 17th ed. Gaithersburg, MD, AOAC.

Atallah, T., F. Andreux, et al. (1995). "Effect of storage and composting on the properties and degradability of cattle manure." Agriculture, Ecosystems and Environment **54**: 203-213.

Bidlack, J., M. Malone, et al. (1992). "Molecular structure and component integration of secondary cell walls in plants." Proceedings of the Oklahoma Academy of Science **72**: 51-56.

Bradford, M. A., G. M. Tordoff, et al. (2002). "Microbiota, fauna, and mesh size interactions in litter decomposition." Oikos **99**: 317–323.

Bussink, D. W. and O. Oenema (1998). "Ammonia volatilization from dairy farming systems in temperate areas: a review." Nutrient Cycling in Agroecosystems **51**: 19-33.

Calderon, F. J., G. W. McCarty, et al. (2004). "Carbon and nitrogen dynamics during incubation of manured soil." Soil Science Society of America Journal **68**: 1592-1599.

Chaney, A. L. and E. P. Marbach (1962). "Modified reagents for determination of urea and ammonia." Clinical Chemistry **8**(2): 130-132.

Diamond, J. (1998). "Ants, crops, and history." Science **281**(5385): 1974-1975.

Dresbøll, D. B., J. Magid, et al. (2006). "Long-term stability and mineralization rate of compost is influenced by timing of nutrient application during composting of plant residues." Compost Science & Utilization **14**(3): 215-221.

Esse, P. C., A. Bueckert, et al. (2001). "Decomposition of and nutrient release from ruminant manure on acid sandy soils in the Sahelian zone of Niger, West Africa." Agriculture, Ecosystems and Environment **83**: 55-63.

Harris, F. (2002). "Management of manure in farming systems in semi-arid West Africa." Experimental Agriculture(38): 131-148.

Havlin, J. L., J. D. Beaton, et al. (2005). Soil Fertility and Fertilizers: An Introduction to Nutrient Management. Upper Saddle River, New Jersey, Pearson Education, Inc.

Kaneko, N. and E. F. Salamanca (1999). "Mixed leaf litter effects on decomposition rates and soil microarthropod communities in an oak-pine stand in Japan." Ecological Research **14**: 131-138.

Lekasi, J. K., J. C. Tanner, et al. (2001). Manure Management in the Kenya Highlands: Practices and Potential, 2nd Edition. High Potential Production System Portfolio of the Natural Resources Systems Programme Renewable Natural Resources Knowledge Strategy Department for International Development. Ryton-on-Dunsmore, The Henry Doubleday Research Association (HDRA): 32.

Lekasi, J. K., J. C. Tanner, et al. (2003). "Cattle manure quality in Maragua District, Central Kenya: effect of management practices and development of simple methods of assessment." Agriculture, Ecosystems and Environment **94**: 289-298.

Licitra, G., T. M. Hernandez, et al. (1996). "Standardization of procedures for nitrogen fractionation of ruminant feeds." Animal Feed Science and Technology **57**(4): 347-358.

Luebbe, M. K., G. E. Erickson, et al. (2008). "Aerobic composting or anaerobic stockpiling of feedlot manure." Nebraska Beef Cattle Reports Retrieved November 22, 2008, from http://digitalcommons.unl.edu/animalscinbcr/25.

Lupwayi, N. Z., M. Girma, et al. (2000). "Plant nutrient contents of cattle manures from small-scale farms and experimental stations in the Ethiopian highlands." Agriculture, Ecosystems and Environment **78**: 57-63.

Martins, O. and T. Dewes (1992). "Loss of nitrogenous compounds during composting of animal wastes." Bioresource Technology **42**: 103-111.

Muck, R. E. and B. K. Richards (1983). "Losses of manurial nitrogen in free-stall barns." Agricultural Wastes 7(2): 65-79.

Murwira, H. K., M. J. Swift, et al. (1995). Animal-soil interactions: Manure as a key resource in sustainable agriculture. Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of sub-Saharan Africa. Vol. II: Technical Papers. Proceedings of an international conference held in Addis Ababa, Ethiopia, 22-26 November 1993. J. M. Powell, S. Fernandez-Rivera, T. O. Williams and C. Renard. Addis Ababa, International Livestock Centre for Africa: 131-148.

Potts, R. C. and P. H. Hewitt (1973). "The distribution of intestinal bacteria and cellulase activity in the harvester termite *Trinervitermes trinervoides* (*Nasutitermitinae*)." Insectes Sociaux **20**(3): 215-220.

Sands, W. A. (1998). The Identification of Worker Castes of Termite Genera from Soils of Africa and the Middle East. New York, CAB International.

SAS Institute Inc (v 9.1). SAS software, Version 9.1.3 of the SAS System for Windows. SAS and all other SAS Institute Inc. product or service names are registered trademarks or trademarks of SAS Institute Inc. Cary, NC, USA, SAS Institute Inc.

Seastedt, T. R. (1984). "The role of microarthropods in decomposition and mineralization processes." Annual Review of Entomology **29**: 25-46.

Van den Boscha, H., J. N. Gitarib, et al. (1998). "Monitoring nutrient flows and economic performance in African farming systems (NUTMON). III. Monitoring nutrient flows and balances in three districts in Kenya." Agriculture, Ecosystems and Environment **71**: 63-80.

Vigil, M. F., B. Eghball, et al. (2002). "Accounting for seasonal nitrogen mineralization: An overview." Journal of Soil and Water Conservation **57**(6): 464-469.

Vossbrinck, C. R., D. C. Coleman, et al. (1979). "Abiotic and biotic factors in litter decomposition in a semiarid grassland." Ecology **60**(2): 265-271.

CHAPTER 3

THE EFFECTS OF SOME EXTERNAL MANAGEMENT FACTORS ON THE QUALITY OF CATTLE MANURE AS A SOIL AMENDMENT ON SMALL FARMS IN KENYA

Abstract

Smallholder farmers in Kenya collect manure from confined cattle housing known as zero-grazing units. Farmers may construct zero-grazing units to collect and conserve urine with the manure, though the effectiveness of these designs in improving manure N content has not been established. The manure-urine mixtures produced by animals housed in these zero-grazing units were simulated to determine the effects of urine on the N composition of manure. Specifically, this study was designed to determine whether most N losses from stored manure occur within the first month of storage, if the presence of urine results in manure with more mineral-N and less fiber-N than manure without urine, if the presence of urine in the manure results in leachate with a larger mineral-N concentration, and to what extent heavy rainfall increases N losses from leaching. Cattle manure was stored with and without urine during dry and rainy seasons in Kenya in a spatially balanced complete block design. Leachate from the manure was collected during the study. Manure was sampled destructively at intervals for 120 days. Urine-amended manure lost 26 % of its initial mineral N content via leaching during the dry season, but only 12 % of the initial mineral N content during the rainy season. The addition of urine to the manure resulted in lower levels of total organic-N and of fiber-N than in manure alone during the dry season ($P < 0.01$), but not in the rainy season. The results suggest that cattle urine has a greater effect on manure composition during dry seasons than during rainy seasons. During the rains, covering manure with a waterproof material should help

conserve manure N by reducing leaching losses. In order to take advantage of the manure N before it is lost due to leaching, manure should not be stored more than 30 days before it is applied to the soil.

Introduction

Smallholder farmers in Kenya who confine their livestock in zero-grazing units collect and store manure for use as a soil amendment throughout the growing seasons (Lekasi, Tanner et al. 2001). The design of zero-grazing units may allow for the collection and preservation of some of the cattle urine. A survey of 60 smallholders in the Kenyan highlands reported more than half of the farms used zero-grazing units with sloped floors and manure storage piles just outside the animal confinement area at the base of the sloped floor. Liquids from the zero-grazing unit floor drained into the manure storage pile. Less than 10 % of farms used designs that allowed direct urine collection such as channels to transfer liquid from the zero-grazing unit floor into a reservoir just outside of the confinement area (Lekasi, Tanner et al. 2001). The animal housing on the remaining farms had no design attributes to conserve urine. The liquid from the floor of the animal confinement area was either absorbed by bedding and feed refusals on the floor of the zero-grazing unit, or soaked into the soil (Lekasi, Tanner et al. 2001; Lekasi, Tanner et al. 2003). That the urine-conserving zero-grazing unit designs actually increase manure N content has not been established. The designs may not prevent urinary N losses via volatilization (Lekasi, Tanner et al. 2001; Lekasi, Tanner et al. 2003).

The N retention efficiency of zero-grazing systems is poor. More than 36 % of N in a mixture of manure and urine may be lost between excretion and the end of storage. Urinary-N losses are greater when no refusals to absorb the urine are on the floor of the zero-grazing unit. Manure and urine N may be lost via leaching when the dirt floors of the zero-grazing units are cleaned out only a few times each year (Rufino, Rowe et al. 2006).

To determine whether the presence of urine increased manure N content, experiments were conducted with manure-urine mixtures similar to those produced on farms with zero-grazing units designed to drain urine into the manure storage piles. In addition to total manure N content, it is important to consider the patterns of transformation of nitrogenous compounds in manure that occur during storage. One objective of this study was to examine the changes in specific manure N fractions resulting from inclusion of urine in manure storage systems. It was hypothesized that most N losses from stored manure occur within the first month of storage. In a study of stockpiled beef cattle manure, N losses of more than 10 % occurred after 42 days of storage (Luebbe, Erickson et al. 2008). A second hypothesis was that manure with urine contains more mineral N and less fiber-N and lignin-N than manure without urine. Urine is a major source of N in stored manure (Tamminga 1992), so stored manure with urine may not be N-limited, allowing manure microbes to degrade the fibrous manure materials more rapidly. The third hypothesis was that manure mixed with urine leaches more mineral N than manure without urine. Large losses of urinary N via leaching and volatilization may occur from manure before its application to soil (Murwira, Swift et al. 1995). Finally, it was hypothesized that heavy rainfall increases N losses from leaching in newly-stockpiled manure, because the rain saturates the manure and the water-soluble N compounds in fresh manure leach from the manure. The effects of season on manure composition and leaching were investigated by starting one experiment during the dry season and one during the rainy season.

Materials and Methods

Experimental design: Manure from two different farms in the Embu area was used to demonstrate the effects of farm and cattle diet management on manure quality. The larger farm maintained a milking herd of approximately 20 cows. The smaller farm milked 4 Holstein-Freisian cattle. The cattle on both farms were fed by the cut-and-carry method, but the cattle of the larger farm were fed energy concentrates and Napier grass (*Pennisetum purpureum*), a relatively high protein forage, more regularly. That the manure differed in terms of total N and OM content was established prior to the start of the dry season experiment to establish the effects of different management regimes on manure composition. Based on the initial manure composition and the management styles of the farms, the larger farm was designated the better-managed farm and the smaller farm the less well-managed farm. Based on the distinction in management quality, manure from the smaller farm will be referred to as "Low quality" and manure from the larger farm will be referred to as "Medium quality" from this point forward. The cattle urine used in the manure storage experiments was collected from the milking herds of both farms and mixed before being used in the experiment. The urine collections lasted approximately 10 days before the start of the dry season experiment and the start of the rainy season experiment. The urine was stored at 4 °C before the beginning of each experiment. At the start of each experiment, samples of the urine were acidified to $pH < 2.5$ using concentrated H_2SO_4 to prevent NH_3 volatilization by microbes (Marini and Van Amburgh 2003). Before NH_4-N analysis, samples were stored at -20 °C.

Two manure storage experiments were conducted, the first beginning in the dry season and carried out for 120 days, and the second beginning early in the long rainy season, ending after 30 days. The two experiments were designed to demonstrate the effects of rainfall on newly established manure storage systems.

Dry season experiment. The dry season manure storage experiment was conducted from January through June 2007 at the Embu office of the Kenya Agricultural Research Institute in Embu, Eastern Province, Kenya. Mid-January usually marks the beginning of the dry season in Embu, so the experiment was started on January 17, 2007. The installation of the dry season experiment marked the beginning of a 2-month period of very dry weather (Figure 3.1).

Five-liter plastic buckets were modified to collect leachate from the manure. The bottom of each bucket was removed and replaced with a circular piece of stainless steel 50-mesh screen with square apertures of 279 μ on a side. Each of the 120 buckets was assigned one to of four treatments and placed in one of four adjacent tables in a spatially-balanced complete block design to ensure spatial homogeneity in the experiment (van Es, Gomes et al. 2007). A standard funnel-graduated cylinder rain gauge was positioned at the center of the tables and rainfall was measured daily. Three replicates of each treatment were incubated. On a fresh weight (FW) basis, 4.8 kg of manure was added to each bucket. A volume of 1.4 L of urine was added to half of the buckets, representing the daily urine volume-to-fecal mass excretion ratio of cattle in water-constrained environments (Vercoe 1967). The urine NH_4-N concentration was 0.03 M. Three buckets from each treatment were randomly selected for destructive sampling after 6, 12, 18, 24, 30, 50, 70, 90, and 120 days of incubation. After sampling, subsamples of the manure were immediately stored at -20 °C.

Rainy season experiment. The rainy season manure storage experiment, to assess the effects of rainfall on newly-installed manure storage units, was installed on April 18, 2007. A preliminary period of ten days of moderate precipitation preceded the onset of the long rainy period in mid-April (Figure 3.1).

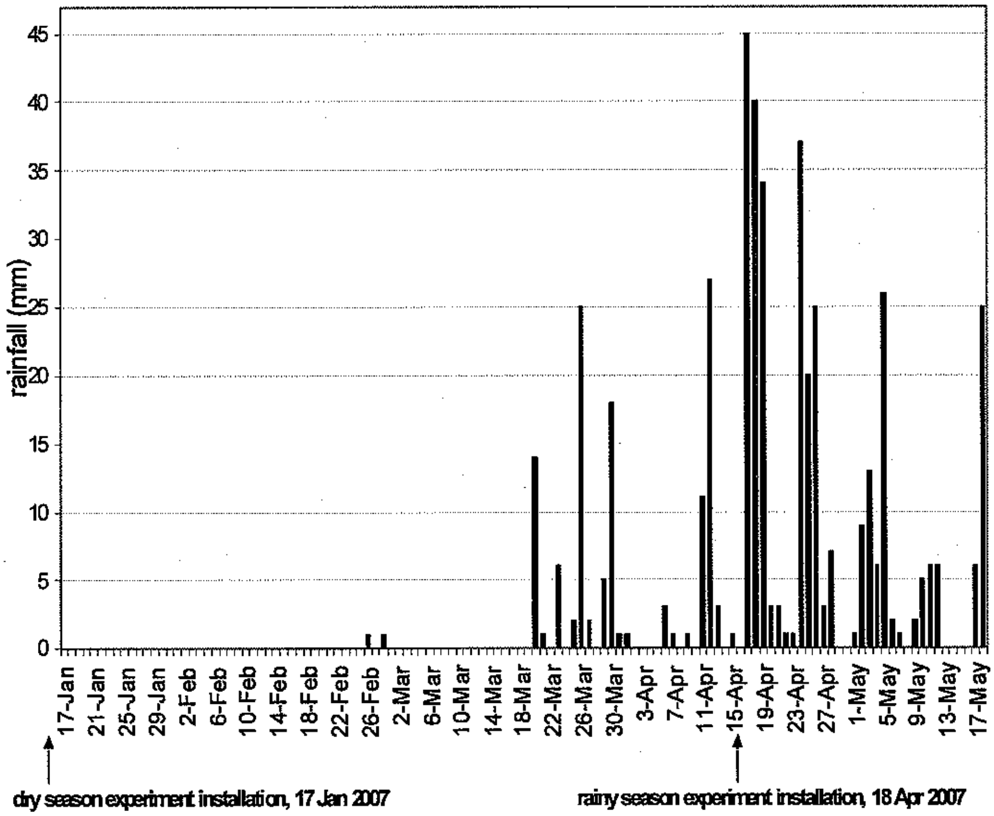


Figure 3.1 Rainfall at the experiment site, Kenya Agricultural Research Institute. Dry season experiment duration: 17 January to 01 June 2007. Rainy season experiment duration: 18 April to 18 May 2007.

The goal of this experiment was to demonstrate the response of newly-stockpiled manure to heavy rainfall. The design of the experiment was similar to that of the dry season experiment. Each of 60 buckets was assigned to one of the four treatments in a randomized complete block design. Three replicates of treatment type were incubated. An initial mass of 4.1 kg (FW basis) of manure was added to each bucket. This initial manure mass differed from the mass used in the dry season experiment because the manure for this study had a greater water content. The manure for the rainy season study was collected early in the long rainy season. The rains dampened manure in the cattle pens before it was collected. An initial volume of 1.2

L of urine was added to half of the buckets, to represent the daily urine volume-to-fecal mass excretion ratio of cattle in water-constrained environments (Vercoe 1967). The NH_4-N concentration of the urine was 0.15 M. The higher NH_4-N content of the rainy season urine likely was because cattle were fed more high protein forages such as Napier grass during the rainy season than during the dry season. Three buckets of each treatment were sampled destructively after 6, 12, 18, 24, and 30 days of incubation.

Leachate collection: For both the rainy and dry season experiments, leachates were collected through a plastic funnel attached to the mesh bottom of each bucket into a 60 mL bottle containing 1 mL concentrated H_2SO_4. The acid immediately lowered the leachate pH to less than 2.5 upon entering the bottle in order to check the degradation of organic and inorganic-N by microbes (Marini and Van Amburgh 2003). The leachate collection bottles were replaced when full and upon the destructive sampling of each bucket. The mass and volume of the leachate collected were recorded. Leachates for each individual bucket were composited by date: after 6, 12, 18, 24, 30, 50, 70, 90, and 120 days of storage for the dry season experiment and after 6, 12, 18, 24, and 30 days of storage for the rainy season experiment.

Chemical analyses: One gram of each frozen subsample was thawed and extracted in 50 mL water for 30 min using an orbital shaker set to 180 rpm. The NH_4-N contents of the extracts were measured using a colorimetric method (Chaney and Marbach 1962) in the soil analysis laboratories of the Kenya Agricultural Research Institute in Embu, Kenya and of the World Agroforestry Centre Headquarters in Nairobi, Kenya.

Aliquots of the manure samples were dried at ≤ 60 °C and ground to pass a 1 mm screen in preparation for analysis. The samples were analyzed at the Dairy One Laboratories, Ithaca New York, USA for total N by the Kjeldahl method (AOAC

2000) and for neutral detergent insoluble N (NDIN) and acid detergent insoluble N (ADIN) (Licitra, Hernandez et al. 1996).

Statistical analyses: The dry and rainy experiments were designed as multi-factor models with fixed effects where the fixed factors were manure quality, urine presence, and days in storage. All possible interactions between the fixed effects were tested. The data were analyzed using the PROC MIXED procedure of the SAS software (SAS Institute Inc v 9.1). Comparisons were made using the Student's t-test.

Using the PROC NLIN procedure of the SAS software (SAS Institute Inc v 9.1), exponential decay models were developed to describe the NH_4-N, total organic N, NDIN, and ADIN the manure in storage over time. Decay models with one exponential term were fitted to the data using the equation $Y = \alpha e^{kx}$, where Y represents the NH_4-N, organic N, NDIN, or ADIN content of the manure, x represents the number of days the manure was incubated in storage, and k represents the rate of decay of the NH_4-N, organic N, NDIN, or ADIN in the manure. Regression of the data using double exponential decay equations failed to converge.

The PROC NLIN procedure of the SAS software was used to develop logarithmic models describing the cumulative NH_4-N losses from manure in storage via leaching (SAS Institute Inc v 9.1). Logarithmic models with one term were fitted to the data using the equation $Y = k\ln(x)$, where Y represents the leached NH_4-N, x represents the number of days the manure was incubated in storage, and k represents the rate of accumulation of the NH_4-N leached from the manure. Regression of the data using log-log equations failed to converge.

Results

Results of the mixed model analyses for the dry season experiment appear in Tables 3.1 – 3.3. The mixed model analyses results for the rainy season experiment appear in Tables 3.4 – 3.6. Cattle feces contain essentially no urea (Muck and Richards 1983; Bussink and Oenema 1998). Cattle urine contains both urea and NH_4. However, since the fecal pH was approximately pH 8, it is assumed that the urea of the urine immediately underwent hydrolysis to produce NH_4 when the urine and manure were mixed. In this study, NH_4-N represents mineral N.

Figure 3.2 shows the NH_4-N dynamics in manure of the dry season experiments. After 30 days of storage, the NH_4-N content of manure alone ranged from 156 to 241 mg NH_4-N per kg of manure (DM basis). The NH_4-N content of urine-amended manure ranged from 372 to 375 mg NH_4-N per kg of manure (DM basis) after 30 days of storage. The manure source had no effect on manure NH_4-N after 30 days or 120 days ($\alpha = 0.05$, Figure 3.2). In the dry season experiment, urine-amended manure treatments manure alone contained less NH_4-N per kg of manure (DM basis) than the treatments with urine after 30 days of storage ($P < 0.04$).

Figures 3.4a-c show the organic N, NDIN, and ADIN dynamics in manure of the dry season experiment. There was no difference in the manure NDIN and ADIN contents after 30 days in storage ($\alpha = 0.05$, Table 3.1), nor was there a difference between the total organic N content of the Medium and Low farm manure after 30 days of storage or at the end of the experiment ($\alpha = 0.05$). NDIN content between the treatments did not differ after 30 days in storage. The days in storage had an affect on the organic N, ADIN, and NDIN contents of the dry season manure over the entire experiment ($P < 0.0001$, Table 3.1), but no treatment effects on total organic N and ADIN were observed after 30 days in storage (Figures 3.4a-c). Single-term exponential decay models for total N, NDIN, and ADIN dynamics in manure appear in Figures 3.4a-c. Exponential decay models using two exponential terms to describe total N, NDIN, and ADIN dynamics in the manure failed to converge.

Single-term logarithmic rate equations describing cumulative leaching of NH_4-N from manure in the dry season experiment appear in Figure 3.6. Logarithmic models with two terms to describe cumulative NH_4-N leaching failed to converge. From each of the 4 treatments, more than 50 % of the final amount of NH_4-N lost from the manure via leaching occurred during the first 30 days of storage.

Exponential decay models to describe the NH_4-N dynamics of the Medium quality manure and Low quality manure in the rainy season experiment using two exponential terms did not converge. Exponential models with one exponential term to describe NH_4-N dynamics appear in Figure 3.3. During the early rainy season, forages are more nutritious and digestible which may explain the marked difference in the NH_4-N content of the urine used in the dry season and rainy season experiments. Neither the source of the manure nor the presence of urine in the manure affected the NH_4-N concentration of the manure in the rainy season experiment ($\alpha = 0.05$) (Table 3.6). Average manure NH_4-N for all treatments after 30 days of storage during the rainy season was 572 mg per kg of manure (DM basis).

In general, lignin-bound N is considered to be quite refractory and poorly available for microbial degradation (Kirk, Connors et al. 1975; Crawford and Crawford 1976). Non-fiber bound nitrogenous organic compounds are more readily available for degradation than hemicellulose-bound N, cellulose-bound N, and lignin-N (represented by NDIN), and cellulose-bound N and lignin-N (represented by ADIN). The portion of the labile organic N that is microbial N can be recycled when a microbe dies and lyses and its cell contents, including nitrogenous compounds, are metabolized by other living microbes.

The magnitude of the N fractions in manure of the rainy season experiment were not affected by urine amendments ($\alpha = 0.05$). After 30 days of storage, the Medium quality manure alone contained 9.2 % organic N, 4.9 % NDIN, and 3.9 %

ADIN (DM basis). The Low quality manure contained 11.0 % organic N, 5.1 % NDIN, and 4.1 % ADIN (DM basis, Figures 3.5a-c). The source of the manure did affect N composition ($P < 0.0001$ for organic N, $P < 0.0001$ for ADIN, $P < 0.0001$ for NDIN) with higher levels of ADIN in the Low quality manure ($P < 0.04$) after 30 days of storage. The time in storage had an effect on the organic N ($P < 0.008$) and ADIN ($P < 0.04$) throughout the experiment, but at the end of the rainy season experiment, the total organic N and ADIN content of the two manures did not differ ($\alpha = 0.05$, Table 3.5). The length of storage had no effect on NDIN ($\alpha = 0.05$). Exponential decay models with one exponential term were developed for total N, NDIN, and ADIN dynamics in manure (Figures 3.5a-c). Decay models with two exponential terms did not converge.

Inclusion of urine significantly increased the amount of NH_4-N leached from manure in the rainy season experiment ($P < 0.0001$). Total NH_4-N losses from urine-amended manure in the rainy season experiment were larger than from urine-amended manure in the dry season experiment. After 30 days of storage during the rainy season, the urine-amended manure storage units lost an average of 337 mg NH_4-N and the storage units containing manure alone lost an average of 97 mg NH_4-N. These cumulative leaching losses represent up to 12 % of the initial manure NH_4-N from urine-amended manure and up to 57 % of the initial manure NH_4-N from manure alone. Neither the manure source nor the urine treatment affected the amount of NH_4-N leached ($\alpha = 0.05$).

After 120 days of storage in the dry season experiment, urine-amended manure lost up to 59 % of its initial DM mass while manure alone lost up to 45 % of the initial DM. These represent mass losses of up to 0.6 kg DM from urine-amended manure and 0.5 kg DM from manure alone after 120 days of storage. At the end of the rainy season experiment, there were no treatment effects on mass loss ($\alpha = 0.05$).

Figure 3.2 shows the NH_4-N dynamics in manure of the dry season experiments. Exponential regression equations with one term to describe the NH_4-N dynamics were developed using manure data for the dry and rainy season experiments (Figures 3.2). Attempted exponential decay models to describe NH_4-N dynamics with two exponential terms did not converge. In the dry season experiment, the manure NH_4-N dynamics fit an exponential decay pattern (Figure 3.2). At the end of 120 days of storage in the dry season experiment, manure NH_4-N fell to less than 200 mg per kg of manure, with the exception of the urine-amended Medium quality manure. In this treatment, the manure NH_4-N content increased after 50 days in storage. At 120 days of storage, the NH_4-N content of the Medium quality manure amended with urine was nearly 400 mg per kg of manure (Figure 3.2). This effect was likely not due to an increase in the pool of NH_4-N in the manure, but the result of an increase in the manure NH_4-N concentration as the manure decomposed. As manure decomposes, its C-containing compounds are converted to CO_2 and CH_4. The loss of C mass reduces the manure C:N, and the concentration of manure N compounds increase (Martins and Dewes 1992).

In the dry season experiment, manure with urine treatments did not contain significantly more NH_4-N at the end of the 120 day experiment than the treatments with manure alone ($\alpha = 0.05$). The manure NH_4-N content averaged 176 mg NH_4-N per kg of manure (DM basis) with a range of 63 to 385 mg NH_4-N per kg of manure (DM basis). The manure source had no effect on manure NH_4-N after 120 days ($\alpha = 0.05$, Figure 3.2).

The presence of urine lowered the fiber-bound N content of the manure in storage. After 120 days of storage during the dry season experiment, the Medium quality manure alone contained 4.9 % NDIN, and 3.9 % ADIN (DM basis). Urine-amended Medium quality manure contained 3.9 % NDIN, and 3.2 % ADIN (DM basis). At the end of the dry season experiment, the Low quality manure alone contained 6.2 % NDIN, and 5.2 % ADIN (DM basis). Low quality manure containing urine contained 5.0 % NDIN, and 4.1 % ADIN (DM basis, Figures 3.4b-c). At the end of the dry season experiment, the Low quality manure contained more NDIN and ADIN than the Medium manure ($P < 0.02$ and $P < 0.03$, respectively). The average organic N content of manure after 120 days of storage was 8.6 % (DM basis). Manure from both sources without urine contained more NDIN at the end of 120 days than did the urine treatments ($P < 0.05$). While the days in storage did have an effect on the organic N, ADIN, and NDIN contents of the dry season manure over the entire experiment ($P < 0.0001$, Table 3.1), total organic N and ADIN did not differ between the treatments after 120 days in storage (Figures 3.4a-c). Exponential decay models with one exponential term were developed for total N, NDIN, and ADIN dynamics in manure (Figures 3.4a-c). Exponential regression with two terms to describe total N, NDIN, and ADIN dynamics in manure failed to converge.

Logarithmic regression using equations with two terms to describe NH_4-N leaching losses did not converge. Cumulative leaching of NH_4-N from manure in the dry season experiment is described by the single-term logarithmic rate equations in Figure 3.6. The presence of urine had a significant positive effect on the amount of NH_4-N leached from manure in the dry season experiment ($P < 0.02$). In total, the urine-amended manure units lost an average of 199 mg NH_4-N while storage units containing only manure lost an average of 104 mg NH_4-N over 120 days of storage. These cumulative leaching losses represents up to 26 % of the initial manure NH_4-N from urine-amended manure and up to 61 % of the initial manure NH_4-N from manure alone. The source of the manure, Low farm or Medium farm, had no effect on NH_4-N leaching rates ($\alpha = 0.05$).

Table 3.1. ANOVA results for N content (DM basis) of manure in storage in the dry season experiment, as a percent of the initial manure N content. Fixed effects are the manure quality (Medium farm vs. Low farm), the presence or absence of urine in the manure, and the number of days the manure was incubated in soil (0, 6, 12, 18, 24, 30, 50, 70, 90, or 120 days). Terms for the interaction between fixed effects are denoted by fixed effects terms separated by an asterisk (*). DF represents the degrees of freedom of the test.

		P - value		
Effect	DF	N (% of DM)	ADIN (% of DM)	NDIN (% of DM)
Medium vs low quality manure [A]	1	0.0218	<0.0001	<0.0001
Urine added vs no urine [B]	1	0.0024	0.0303	0.0052
Days in storage [C]	8	<0.0001	<0.0001	<0.0001
A*B	1	0.0348	0.0875	0.0119
A*C	8	0.0798	0.1258	0.1166
B*C	8	0.0464	0.0092	0.0029
A*B*C	8	0.8771	0.8403	0.3715

Table 3.2. ANOVA results for NH_4-N content (mg NH_4-N / kg manure, DM basis) of manure in storage in the dry season experiment. Fixed effects are the manure quality (Medium farm vs. Low farm), the presence or absence of urine in the manure, and the number of days the manure was incubated in soil (0, 6, 12, 18, 24, 30, 50, 70, 90, or 120 days). Terms for the interaction between fixed effects are denoted by fixed effects terms separated by an asterisk (*). DF represents the degrees of freedom of the test.

		P – value
Effect	DF	NH_4-N (mg / kg manure)
Medium vs low quality manure [A]	1	0.0147
Urine added vs no urine [B]	1	0.0079
Days in storage [C]	9	<0.0001
A*B	1	0.7994
A*C	8	0.5932
B*C	9	0.0199
A*B*C	8	0.0453

Table 3.3. ANOVA results for dry matter (DM) mass remaining in manure in storage in the dry season experiment, as a percent of the initial manure DM mass. Fixed effects are the manure quality (Medium farm vs. Low farm), the presence or absence of urine in the manure, and the number of days the manure was incubated in soil (0, 6, 12, 18, 24, 30, 50, 70, 90, or 120 days). Terms for the interaction between fixed effects are denoted by fixed effects terms separated by an asterisk (*). DF represents the degrees of freedom of the test.

Effect	DF	*P* – value DM mass (% of initial DM mass)
Medium vs low quality manure [A]	1	<0.0001
Urine added vs no urine [B]	1	<0.0001
Days in storage [C]	8	<0.0001
A*B	1	0.8085
A*C	8	0.0058
B*C	8	0.0749
A*B*C	8	0.2125

Table 3.4. ANOVA results for NH_4-N content (mg NH_4-N per manure storage unit) of leachate collected from manure in storage in the dry season experiment. Fixed effects are the manure quality (Medium farm vs. Low farm), the presence or absence of urine in the manure, and the number of days the manure was incubated in soil (0, 6, 12, 18, 24, 30, 50, 70, 90, or 120 days). Terms for the interaction between fixed effects are denoted by fixed effects terms separated by an asterisk (*). DF represents the degrees of freedom of the test.

Effect	DF	*P* – value NH_4-N (mg / storage unit)
Medium vs low quality manure [A]	1	0.4382
Urine added vs no urine [B]	1	0.0192
Days in storage [C]	8	0.0281
A*B	1	0.9802
A*C	8	0.9152
B*C	7	0.3538
A*B*C	7	0.9861

Table 3.5. ANOVA results for N content (DM basis) of manure in storage in the rainy season experiment, as a percent of the initial manure N content. Fixed effects are the manure quality (Medium farm vs Low farm), the presence or absence of urine in the manure, and the number of days the manure was incubated in soil (0, 6, 12, 18, 24, or 30 days). Terms for the interaction between fixed effects are denoted by fixed effects terms separated by an asterisk (*). DF represents the degrees of freedom of the test.

		P - value				
Effect	DF	DM mass (% of initial DM mass)	N (% of DM)	ADIN (% of DM)	NDIN (% of DM)	NH_4-N (mg / storage unit)
Medium vs low quality manure [A]	1	0.1037	<0.0001	<0.0001	<0.0001	<0.0001
Urine added vs no urine [B]	1	0.9842	0.1039	0.1967	0.079	<0.0001
Days in storage [C]	4	0.0004	0.0077	0.0314	0.2868	<0.0001
A*B	1	0.4727	0.009	0.4382	0.2768	<0.0001
A*C	4	0.9315	0.932	0.8198	0.9332	<0.0001
B*C	4	0.5561	0.922	0.9606	0.9683	<0.0001
A*B*C	4	0.7194	0.1104	0.2577	0.435	<0.0001

Table 3.6. ANOVA results for NH_4-N content (mg NH_4-N / kg manure, DM basis) of manure in storage in the rainy season experiment. Fixed effects are the manure quality (Medium farm vs. Low farm), the presence or absence of urine in the manure, and the number of days the manure was incubated in soil (0, 6, 12, 18, 24, or 30 days). Terms for the interaction between fixed effects are denoted by fixed effects terms separated by an asterisk (*). DF represents the degrees of freedom of the test.

Effect	DF	*P* – value NH_4-N (mg / kg manure)
Medium vs low quality manure [A]	1	0.8389
Urine added vs no urine [B]	1	0.2912
Days in storage [C]	5	0.0473
A*B	1	0.1899
A*C	5	0.7942
B*C	5	0.6891
A*B*C	5	0.904

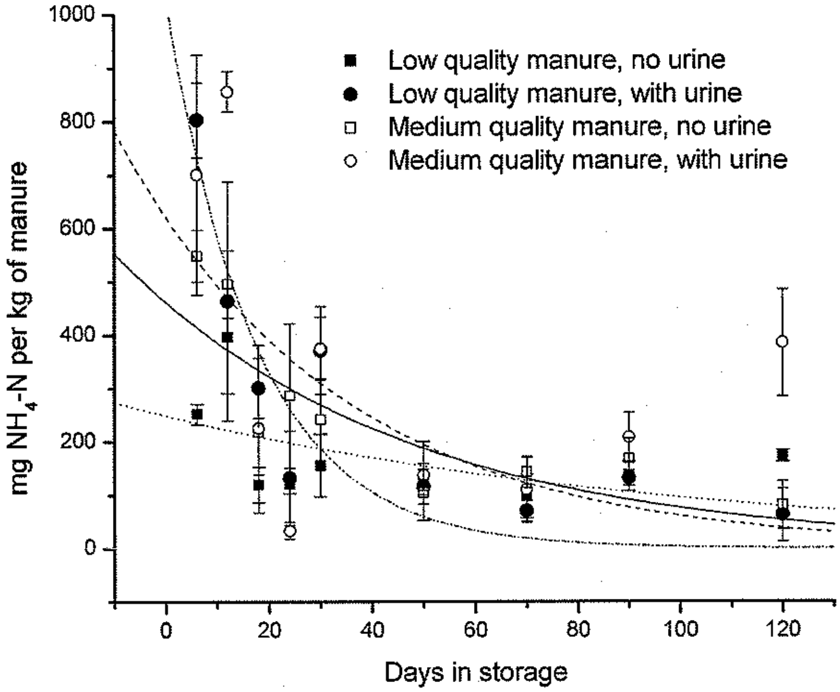


Figure 3.2. NH_4-N dynamics in manure of the dry season storage experiment. Error bars represent standard error of the mean values. Continuous lines represent the best-fit regression equations for NH_4-N dynamics in manure during the dry season experiment. Y represents the amount of NH_4-N (mg / kg manure DM) in the manure. The solid line (——) represents the Medium quality manure, no urine treatment. The dashed line (----) represents the urine-amended Medium quality manure treatment. The dotted line (••••) represents the Low quality manure, no urine treatment. The dot-dash line (-••-••) represents the urine-amended Low quality manure treatment. Medium quality manure, no urine: $Y = 462.3\ e^{-0.0180x}$, $R^2 = 0.807$. Medium quality manure, with urine: $Y = 621.8\ e^{-0.0232x}$, $R^2 = 0.619$. Low quality manure, no urine: $Y = 249.1\ e^{-0.00955x}$, $R^2 = 0.715$. Low quality manure, with urine: $Y = 1033.7\ e^{-0.0570x}$, $R^2 = 0.812$. The rate equations for NH_4-N dynamics between the manure sources did not differ at significance level $\alpha = 0.05$.

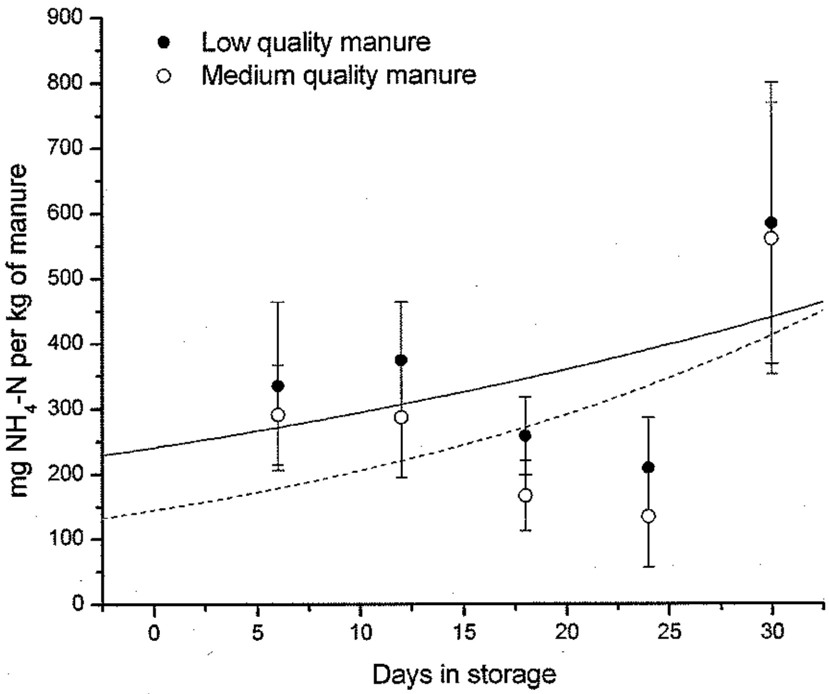
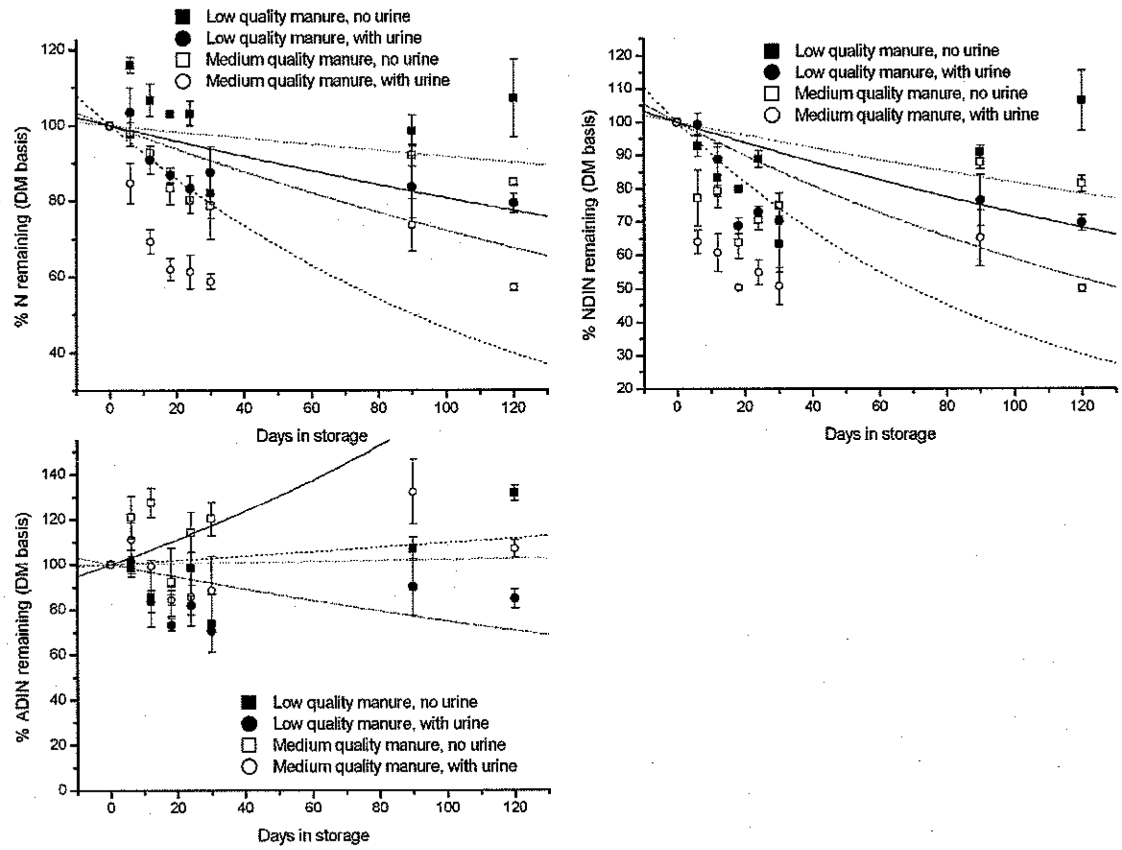


Figure 3.3. NH_4-N dynamics in manure of the rainy season storage experiment. Error bars represent standard error of the mean values. Continuous lines represent the best-fit regression equations for NH_4-N dynamics in manure during the dry season experiment. The solid line (——) represents the best-fit regression for the Medium quality manure treatments. The dashed line (----) represents the best-fit regression for the Low quality manure treatments. Y represents the amount of NH_4-N (mg / kg manure DM) in the manure. Medium quality manure: $Y = 144.7\ e^{0.0349x}$, $R^2 = 0.508$. Low quality manure: $Y = 240.7\ e^{0.0201x}$, $R^2 = 0.571$. The rate equations for NH_4-N dynamics between the manure sources did not differ at significance level $\alpha = 0.05$.

Figure 3.4a-c. Total organic N, neutral detergent insoluble N (NDIN), and acid detergent insoluble N (ADIN) dynamics in manure in the dry season experiment (DM basis). Error bars represent standard error of means. Continuous lines represent best-fit regression equations for organic N dynamics in manure during the dry season experiment. Y represents the amount of organic N, NDIN, or ADIN remaining in the manure (% of initial content, DM basis). The solid line (——) represents the Medium quality manure, no urine treatment. The dashed line (----) represents the urine-amended Medium quality manure treatment. The dotted line (••••) represents the Low quality manure, no urine treatment. The dot-dash line (-••-••) represents the urine-amended Low quality manure treatment. Figure 3.4a (Top left). Total organic N dynamics (% N, DM basis). Medium quality manure, no urine: $Y = 100\ e^{-0.00213x}$, $R^2 = 0.978$. Medium quality manure, with urine: $Y = 100\ e^{-0.00768x}$, $R^2 = 0.916$. Low quality manure, no urine: $Y = 100\ e^{-0.00087x}$, $R^2 = 0.971$. Low quality manure, with urine: $Y = 100\ e^{-0.00372x}$, $R^2 = 0.982$. The rate equations for organic N dynamics between the four treatments did not differ at significance level $\alpha = 0.05$. Figure 3.4b (Top right). NDIN dynamics (% NDIN, DM basis). Medium quality manure, no urine: $Y = 100\ e^{-0.00318x}$, $R^2 = 0.940$. Medium quality manure, with urine: $Y = 100\ e^{-0.00994x}$, $R^2 = 0.823$. Low quality manure, no urine: $Y = 100\ e^{-0.00202x}$, $R^2 = 0.945$. Low quality manure, with urine: $Y = 100\ e^{-0.00529x}$, $R^2 = 0.961$. The rate equations for organic N dynamics between the four treatments did not differ at significance level $\alpha = 0.05$. Figure 3.4c (Bottom left). ADIN dynamics (% ADIN, DM basis). Medium quality manure, no urine: $Y = 100\ e^{0.00528x}$, $R^2 = 0.976$. Medium quality manure, with urine: $Y = 100\ e^{0.000918x}$, $R^2 = 0.970$. Low quality manure, no urine: $Y = 100\ e^{0.000219x}$, $R^2 = 0.951$. Low quality manure, with urine: $Y = 100\ e^{-0.00288x}$, $R^2 = 0.964$. Rate constants for ADIN dynamics in manure with no urine added differed between the manure sources ($P < 0.0001$). No difference was observed in the urine treatments ($\alpha = 0.05$).


Low quality manure, no urine
Low quality manure, with urine
Medium quality manure, no urine
Medium quality manure, with urine
% N remaining (DM basis)
% NDIN remaining (DM basis)
% ADIN remaining (DM basis)
Days in storage

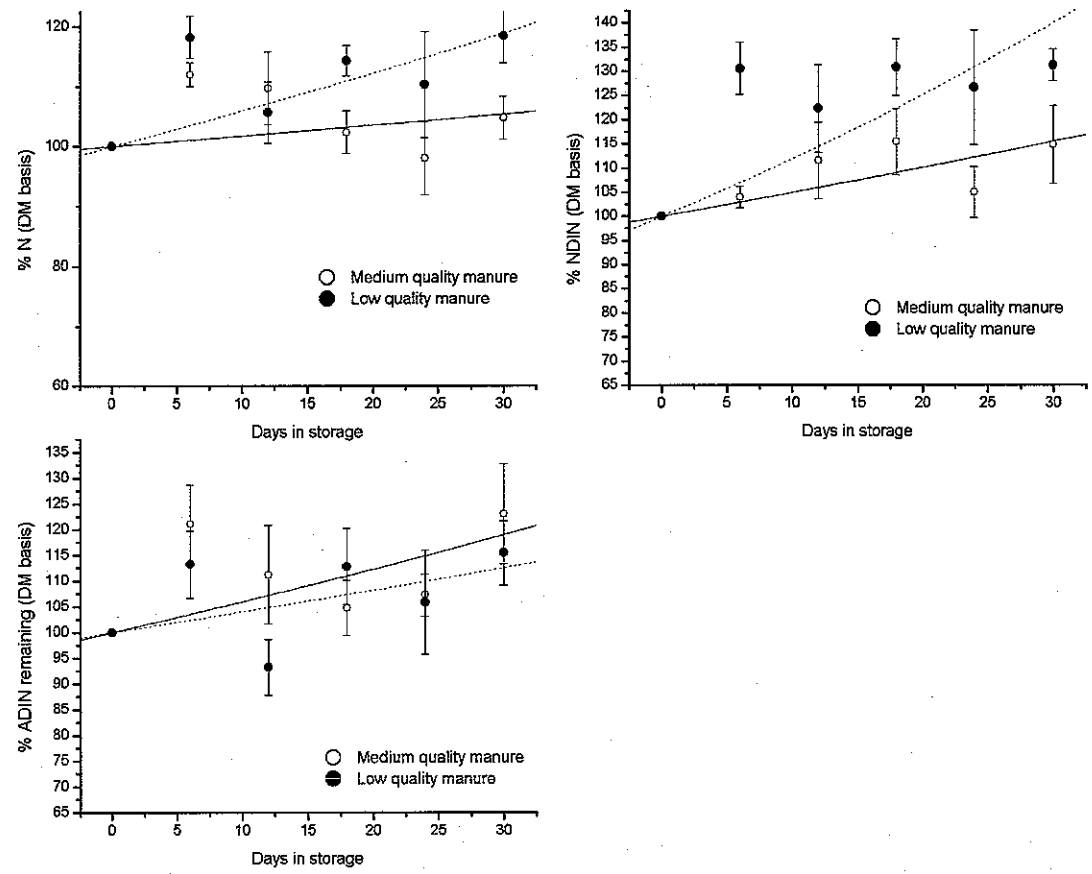


Figure 3.5a-c. Total organic N, neutral detergent insoluble N (NDIN), and acid detergent insoluble N (ADIN) dynamics in manure in the dry season experiment (DM basis). Error bars represent standard error of means. Continuous lines represent regression equations for organic N dynamics in manure during the dry season experiment. Solid lines (——) represent the best fit regression lines for Medium quality manure treatments. Dashed lines (----) represent the best fit regression lines for Low quality manure treatments. Y represents the amount of organic N, NDIN, or ADIN remaining in the manure (% of initial content, DM basis). Figure 3.5a (Top left). Total organic N dynamics (% N, DM basis). Medium quality manure: $Y = 100\ e^{0.00174x}$, $R^2 = 0.989$. Low quality manure: $Y = 100\ e^{0.00576x}$, $R^2 = 0.986$. The rate equations for organic N dynamics between the two manure sources did not differ at significance level $\alpha = 0.05$. Figure 3.5b (Top right). Neutral detergent insoluble N dynamics (% NDIN, DM basis). Medium quality manure: $Y = 100\ e^{0.00478x}$, $R^2 = 0.984$. Low quality manure: $Y = 100\ e^{0.0112x}$, $R^2 = 0.973$. The rate equations for NDIN dynamics between the two treatments did not differ at significance level $\alpha = 0.05$. Figure 3.5c (Bottom left). Acid detergent insoluble N dynamics (% ADIN, DM basis). Medium quality manure: $Y = 100\ e^{0.00578x}$, $R^2 = 0.974$. Low quality manure: $Y = 100\ e^{0.00394x}$, $R^2 = 0.973$. The rate equations for ADIN dynamics between the two treatments did not differ at significance level $\alpha = 0.05$.

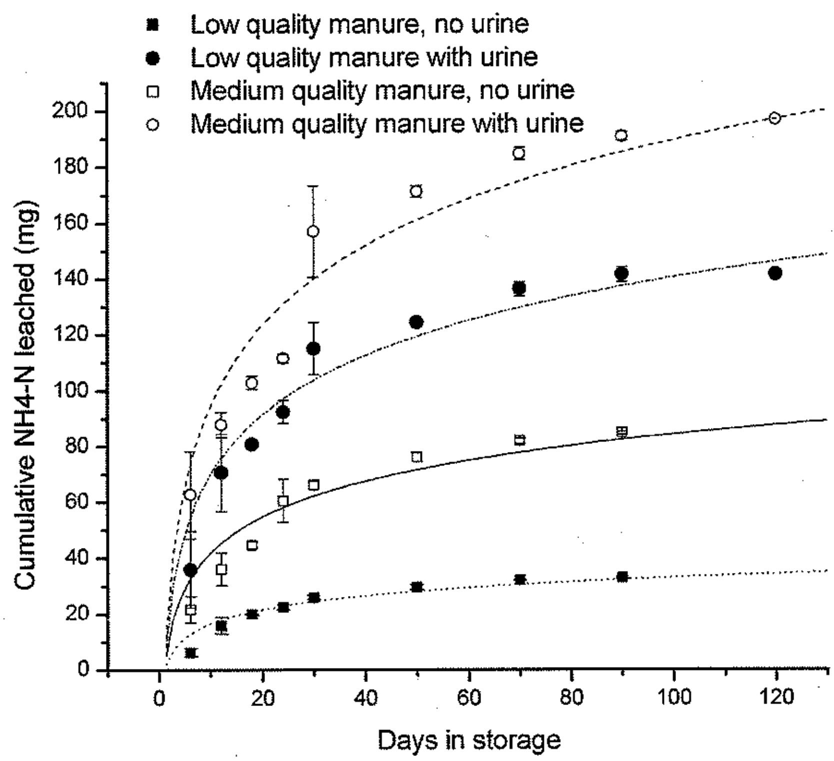


Figure 3.6. Cumulative NH_4-N (mg NH_4-N per manure storage unit) leached from manure of the dry season storage experiment. Error bars represent standard error of the mean values. Continuous lines represent best-fit regression equations for cumulative NH_4-N (mg) leached from manure during the dry season experiment. The solid line (——) represents the Medium quality manure, no urine treatment. The dashed line (----) represents the urine-amended Medium quality manure treatment. The dotted line (••••) represents the Low quality manure, no urine treatment. The dot-dash line (-••-••) represents the urine-amended Low quality manure treatment. Y represents the cumulative NH_4-N (mg) leached from the manure. Medium quality manure, no urine: $Y = 18.3144 \ln(x)$, $R^2 = 0.989$. Medium quality manure, with urine: $Y = 41.1785 \ln(x)$, $R^2 = 0.993$. Low quality manure, no urine: $Y = 7.1964 \ln(x)$, $R^2 = 0.988$. Low quality manure, with urine: $Y = 30.5345 \ln(x)$, $R^2 = 0.994$. The rate equations for leachate NH_4-N between the four treatments did not differ at significance level $\alpha = 0.05$.

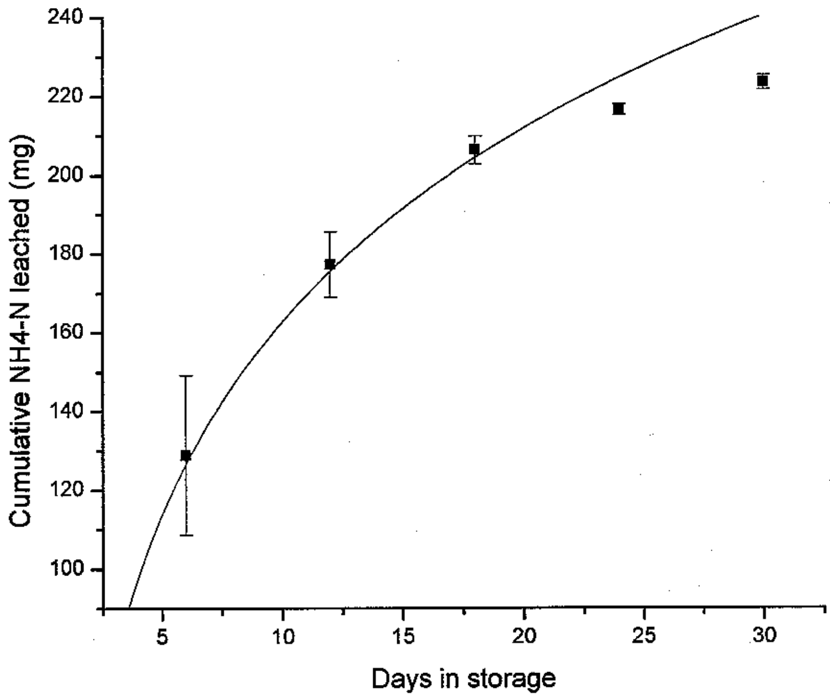


Figure 3.7. Cumulative NH_4-N (mg NH_4-N per manure storage unit) leached from manure of the rainy season storage experiment. Error bars represent standard error of the mean values. The continuous line represents best-fit regression equations for cumulative NH_4-N (mg) leached from manure during the dry season experiment. X represents the number of days in storage. The solid line represents all treatments. Y represents the cumulative NH_4-N (mg) leached from the manure. All treatments: $Y = 70.7127 \ln(x)$, $R^2 = 0.998$.

Discussion

The 14 % greater loss of mass from urine-amended manure observed in this study, a loss of 0.6 kg manure DM in urine-amended manure and 0.5 kg manure DM from manure alone, supports the perception of smallholder farmers that urine speeds up the decomposition of manure in storage (Lekasi, Tanner et al. 2001). In previous studies of composted manure, the manure lost mass over time due to the mineralization of nutrients and other degradation processes that cause structural disintegration (Dresbøll, Magid et al. 2006). In this study, mass loss was observed. The manure continued to lose solid mass after 30 days of storage as a result of microbial activity. Farmers may find the faster degradation of urine-amended manure unacceptable because it results in a smaller volume of manure available to apply to the soil at planting. However, urine may increase the rate of decomposition of the feed refusals in manure, thereby lowering the C:N ratio of the manure and lowering the risk of N immobilization when manure is applied to soil.

The results partially support the hypothesis that most N losses from stored manure occur within the first month of storage. In the dry season and rainy season experiments, NH_4-N losses were large during the first 30 days of storage. In both experiments, the pools of total organic N, the more degradable hemicellulose-bound N, and the refractory fiber-bound and lignin bound N, had increased in concentration by the end of the storage period (Figures 3.4a-c and 3.5a-c). The increase in the concentrations of the N fractions is probably due to manure mass loss: as the manure loses mass over time, the concentrations inflate (Martins and Dewes 1992).

Although some low molecular weight organic-N compounds may have escaped the system via the leachate, the bulk of the loss of the available N is due to the mineralization activities by soil microbes. The labile organic N remaining in the manure after 30 days is likely of microbial origin. The ADIN that remains, 5.1 % of manure DM in the rainy experiment, likely is either part of the lignin fraction or indigestible components of microbial cell walls. The ADIN is very slowly mineralized by microbes (Kirk, Connors et al. 1975; Crawford and Crawford 1976).

The hypothesis that manure containing urine would have more NH_4-N and less fiber-N and lignin-N than manure without urine was only partly upheld by the results of this study. In the dry season, the results were as expected. The presence of urine significantly decreased the organic N content in the manure. This effect may be due to the fact that the urine provides the microbes with a larger pool of NH_4-N for metabolism and growth than the NH_4-N pool in the manure solution alone. The less N constrained environment of urine-amended manure supports larger bacterial populations than that of manure alone, so the microbial degradation of refractory manure compounds is more rapid when urine is present in the manure mixture. The results of another study of stockpiled manure on small Kenyan farms indicated that urine, when added to manure, had no effect on the nutrient composition of the manure (Lekasi, Tanner et al. 2003). This result may have occurred because the manure piles sampled in the study differed in age or because the urinary N was lost to volatilization before being mixed with manure. The manure came from actual manure storage units on many small farms in central Kenya, and manure age was not controlled (Lekasi, Tanner et al. 2003).

Urine may also boost the mineralization of organic N, thereby lowering the total organic N content of the manure, by increasing the water content of the manure. This effect was observed in this study, with urine amendments producing manure with less fiber- and lignin- bound N than manure with no amendments (Figures 3.4b-c). The wetter environment and increased saturation of the manure may allow microbes easier access to sites where organic N is present. Also, solubilization of OM may be facilitated in the more saturated system. Dissolved organic matter (OM) is more easily degraded by microorganisms than solid OM (Said-Pullicino and Gigliotti 2007). The failure of urine to significantly affect the organic N composition of the manure in the rainy season experiment may be due to the fact that the heavy rainfall resulted in urine-amended and non-amended manure with similar water contents, so that any difference between the treatments was obscured (Figures 3.4a-c and 3.5a-c).

The hypothesis that the presence of urine in stored manure would leach a greater volume of leachate with a higher concentration of NH_4-N than manure without urine was supported in the rainy season experiment. Urine did increase the NH_4-N concentration of the leachate in both the dry season and rainy season experiments.

These results suggest measures to prevent leaching losses, such as sheltering the manure from rain and creating a leachate catchment system in which the leachate is collected and returned to the manure pile, should be taken for urine-rich manure in order to conserve manure NH_4-N.

The hypothesis that rainfall increases N losses from manure via leaching was not supported by the data for the urine-amended manure. Total NH_4-N losses from urine-amended manure in the rainy season experiment were 100 mg more (1.5 times greater) than the amount lost from urine-amended manure in the dry season experiment. However, as a percentage of the initial manure NH_4-N content, the urine-amended manure in the dry season lost more NH_4-N than in the rainy season: a loss of 26 % of the initial NH_4-N in the dry season experiment vs. a 12 % loss of the initial NH_4-N in the rainy season experiment. Heavy rainfall increased the volume of the leachate, and the NH_4-N concentration decreased accordingly for the no urine treatments. In spite of this result, the loss of 337 mg NH_4-N from urine-amended manure observed in the rainy experiment is an N loss that should be prevented in order to conserve manure N.

Conclusions

The results suggest the need to protect manure from rain to prevent leaching N losses. Collecting the leachate as it escapes the manure in storage and pouring it back onto the manure would be another way to conserve manure N. If manure is piled on a downhill slope immediately adjacent to fields that require fertilizing, the N-rich leachate may drain into the soil of those fields. If plastic sheeting, an affordable and readily available commodity in Kenya, is first placed on the ground and manure piled on top of it, more of the leachate would drain onto the field. Plastic sheeting could also be used to collect leachate to return to the manure. Contamination of drinking water by uncontrolled leachate runoff and seepage into soil can also be avoided by the use of plastic sheeting. A limitation of using plastic sheeting to collect leachate is the potential for large N losses from the leachate via NH_3 volatilization when the leachate is exposed to air.

Manure that remains in storage for many months continues to lose mass because of microbial activity and compacts due to gravity. The result is manure with far less N than its initial content and less bulk manure to spread on the fields at planting time. To use the manure N before it is lost via leaching, it is recommended that manure not be stored more than 30 days. If the manure cannot be applied to major crops such as maize during the growing seasons, it might be applied to the kitchen gardens. These gardens often contain vegetables that provide important vitamins and minerals to the farm residents. Selling manure to neighboring farms would generate income but could exacerbate the negative nutrient balances observed on most of the farms in the Kenyan highlands.

REFERENCES

AOAC (2000). 954.01 Protein (Crude) in Animal Feed, Forage (Plant Tissue), Grain, and Oilseeds. Official Methods of Analysis of the Association of Official Analytical Chemists, 17th ed. Gaithersburg, MD, AOAC.

Bussink, D. W. and O. Oenema (1998). "Ammonia volatilization from dairy farming systems in temperate areas: a review." Nutrient Cycling in Agroecosystems **51**: 19-33.

Chaney, A. L. and E. P. Marbach (1962). "Modified reagents for determination of urea and ammonia." Clinical Chemistry **8**(2): 130-132.

Crawford, D. L. and R. L. Crawford (1976). "Microbial degradation of lignocellulose: the lignin component." Applied and Environmental Microbiology **31**(5): 714-717.

Dresbøll, D. B., J. Magid, et al. (2006). "Long-term stability and mineralization rate o compost is influenced by timing of nutrient application during composting of plant residues." Compost Science & Utilization **14**(3): 215-221.

Kirk, T. K., W. J. Connors, et al. (1975). "Preparation and microbial decomposition of synthetic [^{14}C]lignins." Proceedings of the National Academy of Sciences **72**(7): 2515-2519.

Lekasi, J. K., J. C. Tanner, et al. (2001). Manure Management in the Kenya Highlands: Practices and Potential, 2nd Edition. High Potential Production System Portfolio of the Natural Resources Systems Programme Renewable Natural Resources Knowledge Strategy Department for International Development. Ryton-on-Dunsmore, The Henry Doubleday Research Association (HDRA): 32.

Lekasi, J. K., J. C. Tanner, et al. (2003). "Cattle manure quality in Maragua District, Central Kenya: effect of management practices and development of simple methods of assessment." Agriculture, Ecosystems and Environment **94**: 289-298.

Licitra, G., T. M. Hernandez, et al. (1996). "Standardization of procedures for nitrogen fractionation of ruminant feeds." Animal Feed Science and Technology **57**(4): 347-358.

Luebbe, M. K., G. E. Erickson, et al. (2008). "Aerobic composting or anaerobic stockpiling of feedlot manure." Nebraska Beef Cattle Reports Retrieved November 22, 2008, from http://digitalcommons.unl.edu/animalscinbcr/25.

Marini, J. C. and M. E. Van Amburgh (2003). "Nitrogen metabolism and recycling in Holstein heifers." Journal of Animal Science **81**: 545-552.

Martins, O. and T. Dewes (1992). "Loss of nitrogenous compounds during composting of animal wastes." Bioresource Technology **42**: 103-111.

Muck, R. E. and B. K. Richards (1983). "Losses of manurial nitrogen in free-stall barns." Agricultural Wastes 7(2): 65-79.

Murwira, H. K., M. J. Swift, et al. (1995). Animal-soil interactions: Manure as a key resource in sustainable agriculture. Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of sub-Saharan Africa. Vol. II: Technical Papers. Proceedings of an international conference held in Addis Ababa, Ethiopia, 22-26 November 1993. J. M. Powell, S. Fernandez-Rivera, T. O. Williams and C. Renard. Addis Ababa, International Livestock Centre for Africa: 131-148.

Rufino, M. C., E. C. Rowe, et al. (2006). "Nitrogen cycling efficiencies through resource-poor African crop-livestock systems." Agriculture, Ecosystems and Environment **112**: 261-282.

Said-Pullicino, D. and G. Gigliotti (2007). "Oxidative biodegradation of dissolved organic matter during composting." Chemosphere **68**(1030-1040).

SAS Institute Inc (v 9.1). SAS software, Version 9.1.3 of the SAS System for Windows. SAS and all other SAS Institute Inc. product or service names are registered trademarks or trademarks of SAS Institute Inc. Cary, NC, USA, SAS Institute Inc.

Tamminga, S. (1992). "Nutrition management of dairy cows as a contribution to pollution control." Journal of Dairy Science **75**: 345–357.

van Es, H. M., C. P. Gomes, et al. (2007). "Spatially-balanced complete block designs for field experiments." Geoderma **140**: 346–352.

Vercoe, J. E. (1967). "Breed and nutritional effects on the composition of faeces, urine, and plasma from Hereford and Brahman x Hereford steers fed on high and low quality diets." Australian Journal of Agricultural Research **18**: 1003-1013.

CHAPTER 4

VARIABILITY OF CATTLE FEEDING ON SMALL FARMS IN KENYA USING THE CUT-AND-CARRY FEEDING METHOD

Abstract

Variability in feeds offered to cattle and daily intake on smallholder farms in Kenya hinder attempts to predict nutrient intake and performance of dairy cattle. An intake study was conducted during each of 4 seasons in Embu, Kenya during 2006 to 2007. Feed offered to cattle on 12 farms in 2 locations and their feed and refusals were weighed and sampled. Feed and refusals samples were analyzed using near-infrared spectroscopy (NIRS). Predictive equations were developed for the nutrient composition of the samples using spectral data and chemical analyses of a subset of the samples by principal components regression (PCR). Using the Cornell Net Carbohydrate and Protein System (CNCPS) Level 1 solution, the effects of limited feed offered and concentrate supplementation on milk production were estimated. Results suggest that the number of animals fed together, preferential feeding of female animals, within-season variation in forage composition, and variations in the amounts of feed offered to and consumed by the cattle are sources of large variation in cattle nutrient intake. Specialty, non-staple forages are fed very infrequently, so their effects on milk production are small. Constrained intake is detrimental to the energy and protein balance of the cow and decreases milk production. In late lactation, because of reduced nutritional requirements, cows are more resilient to poor quality diets. To reduce diet variation, housing animals individually, weighing feeds, and matching herd size to feed availability may be effective strategies. Adding concentrate feed to the diets during early lactation will increase milk production.

Introduction

While the effects of seasonal variation in forage composition and diet composition on milk production on smallholder farms in the Embu region of Kenya have been measured and demonstrated (Nherera 2006), the daily variability in diets has not been quantified in these systems. This purpose of this study was to identify the sources of daily variability in cattle-diet composition in these systems in the same region of Kenya, and to describe the effects of the diet variability on dairy cattle production.

On farms in the Kenyan highlands, daily feed offerings to cattle are based on what is currently available for harvest. For example, farmers who cultivate Napier grass (*Pennisetum purpureum*) with the goal of harvesting high quality forage, cut the grass at 1 m to 1.2 m in height (Orodho 2006). Even with staggered harvesting, intervals with no Napier grass are likely. There are two rainy seasons and two dry seasons per year in the Kenyan highlands. Season and weather conditions affect forage availability and quality. Concentrates, if farmers can afford them, are fed selectively to lactating cows (Nherera 2006). The amounts of feed offered in cut-and-carry systems usually are not measured by weight or volume but rather are estimated by the farmer based on the total amount of forage available and the production level of the individual animal. Because of this imprecise estimation, the daily amount of feed offered and feed consumed is not constant. In a study of North American Holstein cows fed a high quality, balanced ration, up to 22 % of variation in dry matter intake (DMI) was accounted for by diet characteristics and management style. The remaining variation was accounted for by milk yield, body weight (BW), body condition, and temperature (Roseler, Fox et al. 1997). Poor diet quality and variable feeding management mean that diet and management account for a larger portion of the variation in DMI on small Kenyan farms than on farms in North America.

Limited availability of forages and concentrates requires seasonal rationing of feed to cattle. Lactating cows often are the only animals to receive concentrates (Traxler 1997) and usually are offered the best feeds. Farmers feed cows preferentially in order to support milk production, their source of food and income.

The variation in cut-and-carry systems, the scarcity of forages, and the lack of funds to purchase concentrates diminish the quality of livestock diets. In previous studies (Roothaert and Paterson 1997; Melaku, Peters et al. 2003), animals were fed balanced diets and offered pre-determined amounts of feed daily in order to evaluate the nutritive value of forages such as multi-purpose tree fodders, border crops, and vines such as *Lablab purpureus*, *Calliandra calothyrsus*, *Leucaena* spp., and *Sesbania sesban*. These feeds (here referred to as "specialty forages") were used as supplements in the animals' diet. For smallholder Kenyan farms, the production responses reported in these studies may not accurately represent the responses of animals receiving specialty forages because these forages generally are fed in a way does not mimic the feeding system in these research studies. A study in Embu, Kenya, reported most of 41 farms surveyed fed staple forages to cattle during the dry seasons: 100 % of the farms fed maize stover during the dry seasons, 98 % of farms fed banana stover, and 51 % fed local weeds. Only a fraction of the farms fed specialty forages: 22 % of farms fed sweet potato vines and 12 % of farms fed leguminous or non-leguminous tree leaves (Nyaata, Dorward et al. 2000). Another study in the Embu area surveying 45 farms reported that farmers fed *Calliandra calothyrsus* for one-third of the year only (Franzel, Wambugu et al. 2003). The specialty feeds are not important sources of nutrients in dairy diets because of infrequent feeding. This may be because the programs promoting the use of specialty crops such as agroforestry crops may not have reached the farmers (Noordin, Niang et al. 2001), or because farmers have elected not to cultivate the crops because of labor costs.

The goals of this study were to quantify the variability of feed offered and feed intake in cut-and-carry systems on small farms in Kenya, to describe the difference in feeds offered to cattle of different ages and genders, and to estimate the effects of diet composition on milk production. Hypotheses include: a) variability in daily feed offered and intake is greater during the dry seasons than the rainy seasons because of greater scarcity of forages in the dry seasons, b) specialty forages are infrequently offered to cattle and cannot be considered staples in the cattle diets, likely because of insufficient land for non-staple crops or because cash crops such as coffee are priorities, c) female cattle are offered more feed daily and receive more concentrates and high quality forages than male cattle in order to support milk production, and d) the large daily variation in feeds offered to and consumed by cattle results in days on which particularly poor forages or very little feed is offered to cattle. These "poor diet days" will have a much larger negative impact on milk production during early lactation than during late lactation because of higher nutrient requirements to support lactation.

Materials and Methods

Study areas: The study areas were Mukangu and Manyatta sublocations, near Embu in Eastern Province, Kenya, located at 00°S 27' 59" latitude and 037°E 26' 32" longitude. The local altitude ranges between 1500 m to 1760 m above sea level. There are two rainy seasons per year, the long rains from March to June and the short rains from October to December, with annual rainfall averaging 1200 mm to 1500 mm (Nherera 2006). The long dry season is from June to October and the short dry season occurs in January and February.

Study farms: Six farms in Mukangu and 6 farms in Manyatta participated in the study. All farms were participants in the 2001 BASIS-CRSP study (U.S. Agency for International Development, Broadening Access through Strengthening Input Systems Collaborative Research Support Program (BASIS CRSP), "Rural Markets, Natural Capital and Dynamic Poverty Traps in East Africa," 2000-2005). Eleven of the 12 farms also had participated in the 2006 dairy production study (Nherera 2006). The mean farm size was approximately 1.5 ha. Maize, coffee, maize-bean intercrop, and bananas were the main crops grown on the farms. A portion of the farm land was devoted to growing forage crops for cattle consumption (either of the entire plant or the stover). The land area devoted to forages among the Mukangu farms ranged between 0.08 ha and 0.81 ha with a mean of 0.49 ha. Among the Manyatta farms, the area of land under forages varied from 0.12 ha to 1.52 ha with a mean of 0.61 ha.

All of the farm families owned at least one adult cow at the start of the experiment in August 2006. During the four-season intake study, the number of adult cows fed individually ranged from 14 to 16. There was 1 group of 2 adult cows housed and fed together and 1 group of 3 cows housed and fed together throughout the study. Groups of cattle fed together are referred to as "feeding groups" in this paper. Changes in the numbers and types of feeding groups varied from season to season occurred when farmers sold animals, purchased animals, built new zero-grazing units, or restructured existing units. Farmer-reported lactation data were collected during the study. At the beginning of each of 4 forage collection periods (1 collection period per season), farmers were asked by the researchers to report the volume of milk produced by each of the cows on the farm, the length of time each cow had been in lactation, and pregnancy status of each cow. At the beginning of the first forage collection period, during the long dry season, farmers were asked to also report the peak milk production volume of each of their cows. Two cows freshened during the study.

The cows were housed in zero-grazing units with partial cover providing protection from sunlight and rain. The units had either concrete or dirt floors. Some animals were housed individually while others were penned in groups of two or three. All of the animals were fed using the cut-and-carry feeding method. Forages were cut by hand and carried to the animals. The cut forages fell largely into 4 groups of staple feeds: maize stover (*Zea mays*), Napier grass (*Pennisetum purpurerum*), banana stover (*Musa acuminata*), and various grasses and weeds.

Manure cleared from the pens was stored in a heap or pit for up to 6 months before being applied to the soil. On 4 of the farms, manure and bedding from the housing pens were cleared daily, 2 of the farms cleared the pens twice or thrice weekly, on 1 farm the clearing interval was weekly, and on 5 farms the interval was greater than 2 months. Most of the collected manure was applied to maize fields.

Sample collection: The experiment took place from August 2006 through May 2007. Four periods, each of 5 weeks' duration during each of the 4 seasons: long dry season, short rainy season, short dry season, and long rainy season, were designated for sample collection. On each day during a collection period, a member of the research team weighed the amount of each type of forage and concentrate feed offered to each animal using a spring scale. Wherever possible, the animals were fed separately. Every morning, before feeding, refusals were weighed and sampled. Feeds were sampled after harvest by the farmer and before they were offered to the animals. At the beginning of each 5-week collection period, the body condition score (BCS, 5-point scale) of each animal was assessed by the researcher (Elanco Animal Health 1997) and the body weight of each animal was estimated by heart-girth measurement using a weight tape from Northeast DHIA, Ithaca, New York.

The feed and refusals samples were oven-dried at ≤ 60 °C. The dried feed and refusals samples were ground to pass a 1 mm screen with a hammer mill (manufacturer unknown). A subset of the samples was ground in a Wiley cutter mill (Thomas Scientific, New Jersey, USA) after the hammer mill broke irreparably.

Spectroscopy: Samples of dried, ground feed and refusals samples were analyzed using near-infrared spectroscopy (NIRS) at the World Agroforestry Centre in Nairobi, Kenya. Flat-bottomed vials with a diameter of 22 mm were filled with sample to a depth of 4 cm without packing. The filled vials were scanned using the NIR light source of the Multi Purpose Analyzer (Bruker Optic GMBH, Germany). The NIR region is defined as 800 nm to 2500 nm (12,500 cm^{-1} to 4000 cm^{-1}). The scanning occurred in the integrating sphere window using diffuse reflectance mode and an external RT-PbS detector. The scanner velocity was 10 kHz. Thirty-two scans were averaged for each NIR-spectrum. A resolution of 8 cm^{-1} was calculated using a Fourier transform with the apodization function Blackmann Harris 3 Term and a zero filling factor of 2.

The resulting spectral data set is hereafter referred to as FORAGE. After analysis, a subset of the sample set was selected for development of the calibration set by developing a principal component analysis (PCA) model for each sample set, dividing the data set into quartiles using Euclidean distance percentiles calculated from the PC scores, and randomly selecting 10 % of samples from each of the quartiles. The calibration set included 208 samples from FORAGE. Samples identified as calibration samples were analyzed using chemical methods, in addition to the spectral analysis.

Chemical analyses: The calibration samples from FORAGE were analyzed for dry matter (DM), neutral detergent insoluble fiber (NDF), acid detergent insoluble fiber (ADF), and acid detergent lignin (ADL) (Van Soest, Robertson et al. 1991) at Cornell University. These samples were also assayed for total N by the Kjeldahl method (AOAC 2001) and for neutral detergent insoluble protein (NDICP) and neutral detergent insoluble protein (ADICP) (Licitra, Hernandez et al. 1996) at the Dairy One Laboratories, Ithaca, New York, USA.

Statistical analyses: Linear regression models to predict nutritive composition of the feed and refusals were developed using principal components regression (PCR) (Williams and Norris 2001). In the first step of PCR, principal components analysis (PCA) was used to calculate principal components (PCs) from the FORAGE data set using linear combinations of the spectral data that account for large amounts of the variation within the spectral data. The PCs were calculated using PROC FACTOR in SAS v 9.1 (SAS Institute Inc v 9.1). PROC FACTOR centered the spectral data. One hundred significant principal components (PCs) were identified and used in conjunction with the chemical data of the calibration samples to develop linear regression models to predict the chemical composition (DM, OM, NDF, ADF, ADL, NDICP, ADICP, and CP) of the FORAGE data. A multiple linear regression model for each chemical component was developed by stepwise multiple linear regression using the STEPWISE option of PROC REG in SAS (SAS Institute Inc v 9.1). The X-variates were the calibration data and the Y-variates were the PCs. A significance level of $\alpha = 0.1$ was the criterion used by the stepwise regression procedure to determine which x-variates to include in the model after each iteration. In some cases, processing of the data beyond the automatic centering performed by PROC FACTOR was required to produce the best predictive regression model. Table 4.1 lists the data pre-processing used in the development of each regression model. The R^2 values for each regression model are also listed. Models labeled "Centered" used calibration data that were centered only. "Running smooth 11" indicates that the spectral data were smoothed using a running smooth with an interval of 11 wavenumbers (Williams and Norris 2001; Ball 2008). The "First-order difference" label indicates that the spectral data were first smoothed using the 11-wavenumber running smooth and then the first-order difference of the data was calculated using the finite-difference method. Applying the first-order difference to the data can account for variation between spectra due to changes in light source (Williams and Norris 2001). The poor predictability of the regression model for OM resulted in its elimination from further discussion in this paper.

Table 4.1. Processing techniques applied to the FORAGE spectral data to develop predictive regression models for each chemical component. No processing was applied to "Centered" data other than the automatic centering performed by PROC FACTOR. "Running smooth 11"-labeled spectral data were smoothed using a running smooth with an interval of 11 wavenumbers. "First-order difference" indicates that the spectral data were first smoothed using the 11-wavenumber running smooth and then the first-order difference of the data was calculated using the finite-difference method.

Chemical component	Data processing	R^2
DM	Running smooth 11	0.847
OM	First-order difference	0.454
NDF	Running smooth 11	0.974
ADF	Running smooth 11	0.972
ADL	Running smooth 11	0.934
CP	Running smooth 11	0.976
NDICP	First-order difference	0.870
ADICP	Centered	0.926

Because two different grinders were used to process the samples, the spectral data were assessed for systematic differences in the particle size of the ground samples due to grinder type. None of the principal components used in the model accounted for a variation in particle size.

The forage experiment was designed as a multi-factor model with fixed effects where $\alpha_1 - \alpha_2$ represent the fixed factors, feeding group type and season. The fixed effects model used is as follows: $Y_{ijk} = \mu + \alpha_{1i} + \alpha_{2j} + \varepsilon_{ijk}$. The effect of sublocation, Manyatta or Mukangu, was not included on the model because the two sublocations were similar in many respects. First, the sublocations had similar altitudes; they were situated just below the tea zones (1500 m), in the coffee zones. Second, the farms in the two sublocations had similar areas of land under forage cultivation (medians: 0.55 ha in Manyatta and 0.53 ha in Mukangu). Third, the residents of Manyatta and Mukangu are of the same ethnic group, so farm management styles are likely to be similar. The PROC GLM procedure of the SAS software was used for statistical analyses (SAS Institute Inc v 9.1). Comparisons of means were made using the Student's t-test.

Lactation data were analyzed using a multi-factor model with fixed effects to determine the effects on milk production (volume) by the area of farmland under cultivation for forages. In this model, $\alpha_1 - \alpha_2$ represent the fixed factors, the area of land dedicated to forages and stage of lactation (in months). The interaction term represents the effect of the interaction between stage of lactation and land area devoted to forage production on milk production. The fixed effects model used is as follows:

$$Y_{ijk} = \mu + \alpha_{1i} + \alpha_{2j} + (\alpha_1\alpha_2)_{ij} + \varepsilon_{ijk}.$$

Simulations: Feed composition, DMI, animal characteristics, and environmental data from this study and from a 2006 study of cattle in Embu (Nherera 2006) were entered in the Cornell Net Carbohydrate and Protein System (CNCPS) version 5.0.40 (Fox, Tedeschi et al. 2004) to evaluate the effects of variation in diet composition on the milk production of individual cows in early lactation and late lactation during the long dry season. The simulations were performed using the Level 1 solution of the CNCPS to avoid errors associated with the protein and carbohydrate digestion rates and passage rates required for the Level 2 solution. The rates of passage and digestion for dietary protein and carbohydrate used by the Level 2 solution have not been measured for tropical forages. For each of the 4 seasons, the effect on milk production of a "poor diet day" (a day when a cow consumed only low protein feeds and no Napier grass) and the effect on milk production of a "good diet day" (a day when a cow consumed a diet with a large proportion of Napier grass) were estimated for cows in early lactation and cows in late lactation using the CNCPS. The daily diets used in the simulations were actual diets observed during the forage collection periods of the intake study. The effects of concentrate supplements on milk production in early and late lactation were assessed by supplementing the observed diets with 0.5 kg and 1.0 kg of Dairy Meal (as-fed basis) in the CNCPS.

Results

Lactation and BCS data: Farmer-reported lactation data appear in Figure 4.1. Reports of milk production after 14 months were sporadic. The average milk production of cows in month 15 of lactation and beyond was reported by farmers at 4.6 L with a standard error of 1.1. A drop in milk production of approximately 4 L occurred between freshening and the third month of lactation. Cows in late lactation produce less than 5 L per day, while the mean early lactation production was 14.7 L. While lactation stage did affect milk production ($P < 0.02$), no effect of land area was observed ($\alpha = 0.05$). This result further justifies the decision to remove the sublocation effect from the forage model. Although the mean land area under forages differed between the two sublocations, the forage land area did not affect lactation. The BCS data appear in Figure 4.1. The BCS of lactating cattle ranged between 2.0 and 3.0 during the study. The mean BCS for lactating cattle for the entire study period was 2.5.

Feeds offered: A total of 46 individual feeds and feed mixtures were offered to the cattle during this study. Forages most frequently fed included Napier grass (*Pennisetum purpurerum*), maize stover (*Zea mays*), banana leaves and banana stems (*Musa acuminata*), and mixed weeds and grasses. The weeds and grasses were harvested by machete from grass strips along roads and between fields. Because the plants were cut very close to the ground, large amounts of soil may have been included in the cattle diet when weeds and grasses were offered, leading to inflated ash and mineral values. The major concentrates fed to the cattle were dairy meal and bran. Discussion of these most frequently used feeds will be featured in this paper. The frequencies with which feeds were offered, alone or in a mixture, to each feeding group on a daily basis, appears in Table 4.2 as relative frequencies. Frequency values greater than 1 indicate that a feeding group was offered the same type of feed more than once per day.

Feeding groups with only cows were offered Napier grass and concentrate feeds more frequently than those including bulls. When dairy meal was offered to a pen containing female and male cattle, only the cows were allowed to consume it. Napier grass was offered more often during the rainy seasons than during the dry seasons because of greater availability (Table 4.2).

The specialty forages, sorghum stover (*Sorghum* spp.), sugar cane stover (*Saccharum officinarum*), sweet potato vines (*Ipomoea batatas*), *Crotalaria brevidens* and *Calliandra calothyrsus*, when they were offered, were fed to a single feeding group no more than 3 % of the days in a collection period (Table 4.2).

Feed composition: The mean nutrient compositions of the forages fed to cattle, by season, are shown in Table 4.3. Season affected the DM, NDF, ADF, ADL, CP, NDICP, and ADICP of each feed ($P < 0.0001$ for all feed types and components). Large within-season variation in the DM, fiber, lignin, CP, and protein fractionation of each feed was observed (CV values in Table 4.3). Napier grass, banana leaves, weeds and grasses contained the most CP of the available forages, up to 19.7 % CP. Of these three types of forages, the Napier grass contained the least of the most indigestible protein that bound in cellulose and lignin, represented by ADICP.

The NIRS analysis of the concentrate feeds, bran and dairy meal, under-predicted the DM content of these feeds. The results of the laboratory DM and wet chemical analyses were used in the intake calculations. Dairy meal contained 89.4 % DM, 39.9 % NDF, 15.7 % ADF, 4.8 % ADL, 18.6 % CP, 3.1 % NDICP, and 0.7 % ADICP (DM basis). Bran contained 92.0 % DM, 58.7 % NDF, 47.1 % ADF, 20.4 % ADL, 15.7 % CP, 3.5 % NDICP, and 0.6 % ADICP (DM basis). These concentrate feeds have a large CP content, but the NDF content and ADICP content of these concentrate feeds are comparable to those of maize stover, a lower quality forage with a low CP and high NDF content.

Daily intake: The mean FW and DM mass of feed offered daily to the animals in each feeding group and consumed by the animals appear in Table 4.4. Effects of season on the amounts of FW feed offered, FW intake, DM feed offered, and DMI were observed for cows and bulls fed individually ($P < 0.05$). Only for cows fed individually were there differences in the amount of feed offered and in the feeds consumed (FW and DM) between the dry seasons and the rainy seasons. Larger feed offerings (FW and DM) and larger FW intake and DM intake were observed in the dry seasons for cows fed individually, as compared to the rainy seasons (Table 4.4). For bulls fed individually, no difference in the amounts of feed offered (FW and DM) nor in the amounts of feed consumed (DM) was observed between the long dry, short dry, and long rainy seasons ($\alpha = 0.05$). Bulls were offered less feed (DM) and consumed less feed (DM) during the short rainy season than during the other 3 seasons. No seasonal difference in the FW intake of bulls was observed ($\alpha = 0.05$). For cows fed in groups of 2 and 3, no seasonal effects on feeds offered or on intake were observed ($\alpha = 0.05$, Table 4.4).

High variability in the amounts of feeds offered and consumed (FW and DM) in each season by cattle on the study farms, indicated by large coefficient of variation

(CV) values, was observed for cows and bulls in all 4 seasons and in all types of feeding groups. The CV of the observed intake and feeds offered ranged from 34.2 to 83.2 (Table 4.4).

Dietary effects on milk production: The effects of "poor diet days" and "good diet days" were clearly illustrated by the CNCPS simulations using data from the long dry season (Table 4.5). A cow in early lactation may have a negative metabolizable protein (MP) balance of more than 500 g on a "poor diet day" while the negative MP balance is 200 g less when the cow consumes a higher protein diet. In late lactation, a "poor diet day" has a smaller negative impact on the MP balance (Table 4.5). Concentrate supplementation in early lactation elevates the metabolizable energy (ME) balance of the lactating cow from a marginal level into positive energy balance. The effect of concentrate supplements on MP balance was minimal, likely due to the poor quality of concentrate feeds.

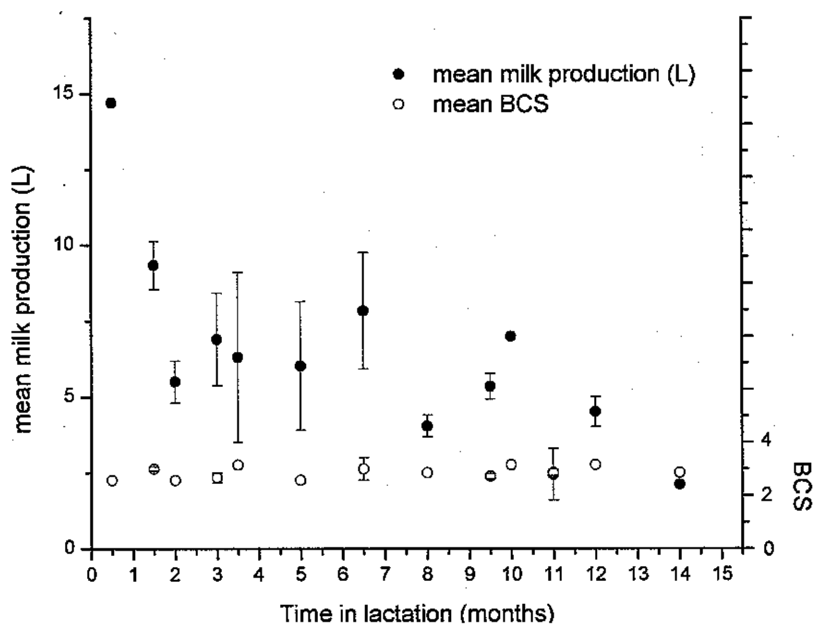


Figure 4.1. Farmer-reported lactation data and BCS data determined by weight-tape measurements for the lactating cows participating in the intake experiment, though 14 mo. of lactation. Error bars represent the standard error of differences in means.

Table 4.2. Relative frequency of offering a feed*, alone or in mixtures, to adult cows and bulls housed individually during the long dry (LD), short rainy (SR), short dry (SD), and long rainy (LR) seasons.

Feed	**Season**	**Animal**	
		Bull	**Cow**
Banana leaves	LD	0.27	0.29
Grass/weeds		0.03	0.06
Maize stover		0.65	0.73
Calliandra calothyrsus		0	0
Banana stems		0.49	0.26
Bran		0.14	0.29
Dairy meal		0	0.30
Napier		0.31	0.41
Crotalaria brevidens		0.01	0
Banana leaves	SR	0.27	0.32
Grass/weeds		0.08	0.14
Maize stover		0.07	0.02
Calliandra calothyrsus		0	0
Banana stems		0.48	0.43
Bran		0	0.46
Dairy meal		0	0.53
Napier		0.88	0.98
Crotalaria brevidens		0.03	0
Banana leaves	SD	0.25	0.23
Grass/weeds		0.21	0.22
Maize stover		0.46	0.30
Calliandra calothyrsus		0.01	0
Banana stems		0.30	0.32
Bran		0	0.52
Dairy meal		0	0.40
Napier		0.71	0.78
Crotalaria brevidens		0.02	0.01
Banana leaves	LR	0.17	0.47
Grass/weeds		0.10	0.25
Maize stover		0.35	0.03
Calliandra calothyrsus		0.01	0
Banana stems		0.46	0.47
Bran		0	0.29
Dairy meal		0	0.45
Sorghum stover		0	0.01
Napier		0.79	0.89
Sweet potato vines		0	0

* Relative frequency of offering a feed = no. of instances offered / (no. of feeding groups x no. of days in collection period). Refer to Table 1 for the distribution of animal groups during each season. Values greater than 1 indicate that the same feed was offered more than once per day to a feeding group.

Table 4.3. Forage composition data for major forages offered to cattle on farms during the long dry (LD), short rainy (SR), short dry (SD), and long rainy (LR) seasons. CV represents the coefficient of variation. DM values are reported as a % of FW. NDF, ADF, ADL, CP, NDICP, and ADICP* values are reported as % of DM.

		DM		NDF		ADF		ADL		CP		NDICP		ADICP	
Feed	Season	mean	CV	mean	CV	mean	CV	mean	CV	mean	CV	mean	CV	mean	CV
Banana leaves	LD	40.8	43.3	54.2	5.7	34.3	17.6	10.8	26.1	13.1	30.5	5.9	28.1	1.4	36.7
Banana leaves	SR	30.9	52.4	50.1	5.9	40.8	12.5	7.0	34.5	18.9	16.8	7.6	19.2	1.0	37.6
Banana leaves	SD	38.3	46.3	48.1	13.8	33.7	21.9	7.7	28.6	15.0	32.4	6.1	30.6	1.1	56.6
Banana leaves	LR	31.7	40.9	50.3	10.3	36.8	20.2	9.7	38.5	19.7	28.1	6.7	26.6	1.1	58.7
Banana stems	LD	18.4	66.0	44.9	17.4	35.7	15.3	6.6	28.8	4.1	76.5	2.8	30.5	1.5	35.5
Banana stems	SR	18.4	59.6	47.0	17.8	36.7	18.0	6.8	34.0	4.3	89.1	3.8	38.7	1.5	31.3
Banana stems	SD	16.8	89.5	42.9	18.4	37.7	19.5	5.3	24.8	2.4	51.5	2.9	36.3	1.1	33.1
Banana stems	LR	12.1	80.9	42.8	22.3	38.7	30.2	6.9	38.8	6.3	60.7	2.9	55.1	1.1	66.4
Banana stems and leaves	LD	38.5	33.0	50.3	8.4	38.9	20.4	8.3	45.7	12.4	15.9	4.9	41.8	1.6	42.1
Banana stems and leaves	SR	27.0	37.8	50.9	9.7	39.1	20.7	7.9	27.9	13.6	41.9	5.6	28.9	1.6	25.8
Banana stems and leaves	SD	39.6	24.2	51.6	6.8	35.8	19.2	8.3	18.6	13.1	23.2	5.9	13.5	0.8	62.9
Banana stems and leaves	LR	27.3	38.9	50.6	12.7	38.6	22.4	9.6	23.0	14.8	25.7	5.9	19.2	1.2	49.0
Grass/weeds	LD	44.8	36.4	60.3	9.2	34.5	9.2	11.7	15.2	12.9	31.2	2.9	36.7	1.6	45.0
Grass/weeds	SR	50.5	46.2	56.5	8.2	37.1	18.7	8.7	33.9	16.4	33.5	4.5	39.2	1.2	43.7
Grass/weeds	SD	40.4	40.5	61.0	12.7	37.0	18.0	10.1	28.1	11.5	39.0	3.8	36.3	1.2	51.5
Grass/weeds	LR	44.6	41.2	56.4	10.5	35.1	22.6	11.1	27.6	16.2	32.0	3.5	34.9	1.3	42.4
Maize stover	LD	45.3	23.2	64.9	8.8	35.7	18.6	7.4	25.2	6.0	34.4	2.3	47.8	0.8	31.0
Maize stover	SD	43.1	30.3	62.9	10.5	35.5	18.9	7.2	34.3	7.8	35.3	2.8	38.3	0.4	77.3
Maize stover	LR	29.9	58.6	68.9	4.8	45.2	18.1	8.3	12.7	6.3	33.6	3.1	---	1.0	36.9
Napier grass	LD	39.0	42.2	62.9	4.7	36.7	16.5	8.0	30.7	12.6	20.3	3.8	27.1	0.9	40.8
Napier grass	SR	25.6	45.9	64.5	6.4	37.9	19.4	6.6	37.4	11.9	29.1	3.9	22.6	0.8	44.7
Napier grass	SD	34.6	35.3	64.6	6.6	37.0	17.4	7.0	27.1	11.4	23.1	3.7	23.5	0.5	51.5
Napier grass	LR	23.0	44.8	63.0	5.8	37.9	22.0	8.6	20.5	13.7	20.6	4.1	28.8	1.0	48.0

*DM = Dry matter; NDF = Neutral detergent insoluble fiber; ADF = Acid detergent insoluble fiber; ADL = Acid detergent lignin; CP = Crude protein; NDICP = Neutral detergent insoluble crude protein; ADICP = Acid detergent insoluble crude protein

Table 4.4. Daily FW and DM feed offered to cattle and the daily FW and DM feed consumed by cattle on the study farms in the long dry (LD), short rainy (SR), short dry (SD), and long rainy (LR) seasons. Values represent the total mass of feed (FW or DM) offered to the animal or group of animals. CV represents the coefficient of variation. Within a single column of mean values (FW feed offered, FW intake, DM feed offered, and dry matter intake (DMI)) and an individual feeding group, mean values with different superscripts differ at a significance level of $\alpha = 0.05$.

Feeding group	Season	FW feed offered (kg)		FW intake (kg)		DM feed offered (kg)		DMI (kg)	
		Mean	CV	Mean	CV	Mean	CV	Mean	CV
1 Bull	LD	12.7^{a}	35.0	12.4^{a}	35.3	4.3^{a}	65.9	4.2^{a}	66.3
	SR	14.3^{b}	36.5	14.3^{a}	36.9	3.8^{b}	52.4	3.8^{b}	52.7
	SD	15.3^{a}	42.9	15.0^{a}	43.9	5.7^{a}	69.0	5.5^{a}	69.1
	LR	17.0^{a}	34.2	17.0^{a}	34.2	3.9^{a}	59.7	3.9^{a}	59.7
1 Cow	LD	16.6^{a}	58.9	15.6^{a}	59.9	6.9^{a}	67.8	6.7^{a}	68.3
	SR	16.4^{b}	61.2	16.2^{b}	61.9	4.4^{b}	67.7	4.4^{b}	68.4
	SD	18.4^{a}	62.2	18.1^{a}	62.8	6.7^{a}	82.2	6.6^{a}	83.2
	LR	16.1^{b}	54.6	15.9^{b}	55.3	4.1^{b}	75.5	4.1^{b}	76.5
2 Cows	LD	21.2^{a}	59.0	19.2^{a}	56.8	11.5^{a}	46.9	10.8^{a}	45.1
	SR	27.2^{a}	67.1	26.5^{a}	67.2	11.0^{a}	64.1	10.8^{a}	63.5
	SD	21.8^{a}	66.7	21.6^{a}	66.5	8.5^{a}	65.7	8.4^{a}	65.8
	LR	26.8^{a}	62.5	26.7^{a}	62.4	7.7^{a}	81.6	7.6^{a}	81.9
3 Cows	LD	30.8^{a}	42.5	30.7^{a}	42.3	11.6^{a}	54.9	11.5^{a}	54.5
	SR	35.5^{a}	55.7	35.5^{a}	55.7	8.5^{a}	60.4	8.5^{a}	60.4
	SD	42.8^{a}	58.5	42.7^{a}	58.8	14.8^{a}	71.8	14.7^{a}	71.7
	LR	55.9^{a}	53.3	55.9^{a}	53.3	13.8^{a}	60.5	13.8^{a}	60.5

Table 4.5. Results of diet simulations using the CNCPS Level 1. Metabolizable energy (ME) balance and metabolizable protein (MP) balance calculations were based on the DMI measured by the researcher. Concentrate supplements were added to the observed intake of cows in early lactation and in late lactation on the study farms during the long dry season.

Lactation stage	Good / Bad diet day	Concentrate supplementation (kg Daily Meal, As Fed basis)	Observed DMI (kg)	Predicted DMI (kg)	ME balance (Mcal/day)	MP balance (kg/day)
Early	Good diet day	0.0	12.7	8.1	-0.9	-0.31
		0.5	13.1	8.1	0.22	-0.29
		1.0	13.6	8.1	1.3	-0.27
Late	Good diet day	0.0	16.8	7.9	11.4	-0.21
		0.5	17.2	7.9	12.4	-0.19
		1.0	17.7	7.9	13.5	-0.17
Early	Bad diet day	0.0	12.8	8.1	0.8	-0.51
		0.5	13.2	8.1	1.88	-0/50
		1.0	13.7	8.1	2.96	-0.48
Late	Bad diet day	0.0	12.9	7.9	6.77	-0.28
		0.5	13.3	7.9	7.87	-0.26
		1.0	13.8	7.9	8.95	-0.25

Discussion

Sources of variation in cattle intake lie in the variability of feed composition, the variability of the mass of feed offered each day to the animals, and the daily variability in the types of feed offered. The highly variable nature of the diets makes prediction of daily intake in these systems very difficult. Preferential feeding, competition among animals for feed, shifting animal groups, and the area of farmland used for forage crops further complicate prediction of cattle intake on smallholder farms.

Variations in forage and concentrate feed composition from season to season have been observed on some of the same small farms in the Embu area (Nherera 2006). This study also showed large variations in the composition of forages and concentrates within each season (Table 4.3). Large within-season variability in feed offered and intake were observed in this study (Table 4.4), but the hypothesis that the amounts of feed offered and consumed vary more in dry seasons was not supported. While feeds offered and intake (FW and DM) were smaller during the rainy seasons for individually-fed cows and smaller during the short rainy season for bulls fed individually, the CV of the observed amounts of feeds offered to and consumed by cattle were very large in all 4 seasons and in all feeding groups (Table 4.4). No seasonal differences in CV were observed.

Specialty forages such as *Crotalaria brevidens*, *Calliandra calothyrsus*, sweet potato vines, and sorghum stover were offered very infrequently, no more than 3 % of the time. Sorghum stover and sweet potato vines were offered only during the long rainy season. This result supports the hypothesis that specialty forages should not be considered staples in the cattle diet.

Studies evaluating the impact of specialty forages on cattle production (Roothaert and Paterson 1997; Melaku, Peters et al. 2003) should consider the infrequent feeding of such feeds before reporting production results to smallholder farmers in Kenya. Any reports of the benefits of specialty forages should include strategies to encourage farmers to offer the feeds more regularly, ideally on a daily basis.

Preferential feeding was evident on the study farms in that cows were offered and consumed more concentrates and high-quality forages (high in protein not bound to lignin, low in lignin and other indigestible structures). However, adult cows were not offered more total feed than adult bulls. Offering cows more of the concentrates and high-quality forages, such as Napier grass, to cows was expected since farmers want to support milk production for family nutrition and for profits when excess milk is sold. That no difference was observed between total mass of feeds offered to bulls and cows or between the intake of bulls and cows was unexpected. Lactating cows have larger intake requirements than bulls to support the daily expenditure of energy and nutrients involved in milk production. Bulls are used for traction on small Kenyan farms, but this work is not continuous. Bulls may be used daily for a short time at planting and intermittently for transportation. During these times, the bulls' higher nutrient requirements may exceed their intake and the bulls may lose body reserves. However, in the days after a period of work, bulls compensate for their loss of body reserves by increasing their intake (Pearson and Dijkman 1994).

Competition for food between cattle in group housing leads to formation of a feeding hierarchy (Wierenga 1990). An individual's position in the hierarchy affects its daily feed intake. In a study of groups of 12 Holstein cows on a Canadian dairy facility, the animals most dominant in the hierarchy, often mature cows, spent more time than the less dominant animals during the 2 hours after the time fresh feed was offered (Val-Lalliet, de Passille et al. 2008). On small farms in Embu, forages are often not chopped or mixed before they are offered to the cattle. Dominant animals within feeding groups likely have access to the choicest, most nutritious forages and the subordinate animals are left with the lower quality forages. Also, the subordinate animals may be repeatedly ousted from their place at the feeding trough by the dominant animals (Olofsson 1999). As a result, the subordinate animals have less time to eat.

Competition for feed in multi-animal feeding groups in the smallholder farm system may be compounded by the effect of group size on the mass of feed offered by the farmers. Multi-animal groups tended to be fed less than the sum of what their animals were fed when housed individually. For example, 2 cows housed together received 10.8 kg DM in the long dry season and 8.4 kg in the short dry season while individually housed cows received an average of 6.7 kg DM and 6.6 kg DM in the long dry and short dry seasons, respectively. The feeds offered daily to the individually housed cows and the cows' DMI during the dry seasons fall within the range of DMI predicted for lactating cattle on small farms in Embu, 8.4 ± 2.4 kg DM (Nherera 2006). The rainy season offerings and DMI values do not meet these observed values. Neither the offered feeds, DMI during the dry seasons nor those of the rainy seasons meet the recommended 9.4 kg DMI for small breed cattle (BW of 454 kg) in early lactation, producing 15 kg milk at 4.0 % milk fat (National Research Council 2001). Three cows together were offered 11.5 kg DM feed daily in the long dry season and 14.7 kg DM in the short dry season. Two cows housed together were fed less than twice what individual cows were offered. Three cows together were offered approximately twice what a single cow was offered. It appears that farmers gauge feed mass for multiple-animal feeding groups on a different and less generous scale than the one used to judge feed for animals housed alone. The distribution of feeding groups changed from season to season, so animals may move back and forth between an individual housing unit where their intake requirement is met to group housing with insufficient feeds offered and competition between the animals for feed. The simulation results suggest that cows are in a negative MP balance and a marginal ME balance in early lactation. Adding small amounts of concentrate feeds such as dairy meal to the diet, up to 1 kg, can increase the ME balance by up to 2.1 Mcal / day. The negative effects of a "poor diet day" during early lactation on the MP balance may have devastating consequences on milk production. Figure 4.1 shows a large drop in milk production within the first 2 months of lactation. Several "poor diet days" may cause a drop in lactation from which the cow never recovers.

Supplementing diets with concentrates and high protein forages may make the early decline in milk production less severe. Since concentrates are costly, farmers allocate concentrates only to cows producing large volumes of milk, which are most often cows in early lactation only. Concentrate supplementation has a lesser effect on ME balance during late lactation, even during "poor diet days" (Table 4.5). Feeding concentrates during early lactation seems to be more important to supporting milk production than feeding concentrates during late lactation, although late lactation supplementation may help cows build up body condition in support of calving and their next early lactation phase.

Conclusions

Beyond seasonal variations in forage composition, there are other large sources of variability in the composition of cut-and-carry cattle diets on smallholder farms in Kenya. Preferential feeding of high-quality feeds, within-season variations in forage composition, within-season variations in the amounts of feed offered and in the feed intake, feeding group dynamics, and competition within feeding groups contribute to the unpredictability of cattle nutrient intake. These numerous sources of variation present large obstacles to modeling cattle nutrient intake and growth to improve milk production. Also hindered by the wide diet variability is the prediction of improvements to dairy production by the introduction of specialty forages into the animal diet. Infrequent feeding of specialty forages makes assessment of their value to improving milk production difficult.

Farmers may take some steps to decrease the variability in the diets of their cattle. To remove the effects of competition and feeding group structure on the amounts of feed offered, animals could be housed individually. This option depends on available cash resources for zero-grazing unit construction. More equitable feeding might also be achieved by weighing feeds with a spring scale before offering to make sure animals in multi-animal groups are fed as equitably as possible. None of the participating farms owned a spring scale before the study began, so the cost of a scale may be prohibitive to farmers. Feeds might also be measured by volume using a large bucket. Measuring feeds will increase the labor associated with feeding, which may be unacceptable to some farmers. Competition will still be a source of variation in this scenario. Farmers could reduce their herd size to ensure sufficient available feeds to meet their animals' growth and production requirements. However, small herd sizes mean fewer animals to serve as savings that can be liquidated when ready cash is needed. Farmers may not be willing to make this trade-off. An extra concentrate supplement for cows in early lactation may be another means of supporting milk production. Days when cows' nutrient consumption is constrained, or "poor diet days", are detrimental to milk production.

The variation in cattle diets on small Kenya farms may obstruct attempts to model and improve dairy cattle nutrition and production. Efforts to measure feeds offered, to feed concentrates preferentially to high-producing cows, and to reduce the size of cattle feeding groups, should be made by farmers to eliminate sources of variation in the cattle diet and to increase milk production.

REFERENCES

AOAC (2000). 954.01 Protein (Crude) in Animal Feed, Forage (Plant Tissue), Grain, and Oilseeds. Official Methods of Analysis of the Association of Official Analytical Chemists, 17th ed. Gaithersburg, MD, AOAC.

Ball, J. I. (2008). Use of Visible-Near Infrared Spectroscopy for the assessment of soil quality indicators. M.S. Thesis, Cornell University, Ithaca, New York.

Elanco Animal Health (1997). Body Condition Scoring in Dairy Cattle Bulletin AI 8478 (Rev. 3/04). Indianapolis, IN.

Fox, D. G., L. O. Tedeschi, et al. (2004). "The Cornell Net Carbohydrate and Protein System model for evaluating herd nutrition and nutrient excretion." Animal Feed Science and Technology **112**: 29-78.

Franzel, S., C. Wambugu, et al. (2003). "The adoption and scaling up of the use of fodder shrubs in central Kenya." Tropical Grasslands **37**: 239-250.

Licitra, G., T. M. Hernandez, et al. (1996). "Standardization of procedures for nitrogen fractionation of ruminant feeds." Animal Feed Science and Technology **57**(4): 347-358.

Melaku, S., K. J. Peters, et al. (2003). "In vitro and in situ evaluation of selected multipurpose trees, wheat bran and *Lablab purpureus* as potential feed supplements to tef (*Eragrostis tef*) straw." Animal Feed Science and Technology **108**: 159-179.

National Research Council (2001). Nutrient Requirements of Dairy Cattle, Seventh Revised Edition. C. o. A. N. Subcommittee on Dairy Cattle Nutrition, Board on Agriculture and Natural Resources. Washington D.C., National Academy Press.

Nherera, F. V. (2006). Predicting energy and protein supply and milk production of dairy cows consuming high forage rations in the eastern highlands of Kenya. Cornell University, Ithaca, New York. **Ph.D. Dissertation.**

Noordin, Q., A. Niang, et al. (2001). "Scaling up adoption and impact of agroforestry technologies: experiences from western Kenya." Development in Practice **11**(4): 509-523.

Nyaata, O. Z., P. T. Dorward, et al. (2000). "Availability and use of dry season feed resources on smallholder dairy farms in central Kenya." Agroforestry Systems **50**: 315-331.

Olofsson, J. (1999). "Competition for total mixed diets fed for ad libitum intake using one or four cows per feeding station." Journal of Dairy Science **82**: 69-79.

Orodho, A. B. (2006). "The role and importance of Napier grass in the smallholder dairy industry in Kenya." Retrieved September 1, 2008, from http://www.fao.org/ag/AGP/AGPC/doc/Newpub/napier/napier_kenya.htm.

Pearson, R. A. and J. T. Dijkman (1994). "Nutritional implications of work in draught animals." Proceedings of the Nutrition Society **53**: 169-179.

Roothaert, R. L. and R. T. Paterson (1997). "Recent work on the production and utilization of tree fodder in East Africa." Animal Feed Science and Technology **69**: 39-51.

Roseler, D. K., D. G. Fox, et al. (1997). "Development and evaluation of equations for prediction of feed intake for lactating Holsten dairy cows." Journal of Dairy Science **80**(5): 878-893.

SAS Institute Inc (v 9.1). SAS software, Version 9.1.3 of the SAS System for Windows. SAS and all other SAS Institute Inc. product or service names are registered trademarks or trademarks of SAS Institute Inc. Cary, NC, USA, SAS Institute Inc.

Traxler, M. J. (1997). Predicting the effect of lignin on the extent of digestion and the evaluation of alternative intake models for lactating cows consuming high NDF forages. Department of Animal Science. Ithaca, New York, Cornell University. **Ph.D. Dissertation:** 145.

Val-Lalliet, D., A. M. de Passille, et al. (2008). "The concept of social dominance and the social distribution of feeding-related displacements between cows." Applied Animal Behaviour Science **111**: 158-172.

Van Soest, P. J., J. B. Robertson, et al. (1991). "Methods of dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition." Journal of Dairy Science **74**(10): 3583-3597.

Wierenga, H. K. (1990). "Social dominance in dairy cattle and the influences of housing and management." Applied Animal Behaviour Science **27**: 201-229.

Williams, P. and K. Norris, Eds. (2001). Near-Infrared Technology in the Agricultural and Food Industries. St. Paul (MN), American Association of Cereal Chemists.

CHAPTER 5
SUMMARY

The studies of cattle manure management and the cut-and-carry feeding system on smallholder farms in the highlands of Kenya described in this dissertation provide several practical suggestions to farmers. First, the long periods of manure storage common on small Kenyan farms produce manure with little mineral N. Most of the mineral N is lost from manure storage systems during the first 30 days of storage. It is recommended that manure be left in storage no longer than 3 weeks. In this way, the conserved mineral N in the manure will become available to plants when the manure is applied to the soil. Shorter storage periods also allow farmers avoid the considerable mass loss that occurs during storage, beyond 50 % of the mass after 120 days, so they have more manure available to apply to soil. More frequent applications of manure to soil require more labor for the farmer, which may cause some farmers to refuse to adopt the shorter manure storage periods.

Second, efforts should be made to protect manure from rainfall and leaching. Leaching is a major avenue for mineral N loss from manure in storage, up to 26 % of the initial mineral N content of the manure. Covering storage piles with plastic sheeting will protect manure from rainfall. To prevent leaching losses from the storage system, manure piles could be constructed on plastic sheeting. The leachate may be collected and returned to the pile or it may be applied to kitchen garden or forage crops.

An obstacle to improving cattle diet on small Kenyan farms is the variability of diets in the cut-and-carry livestock feeding system. The seasonal variation in forage composition is well-established. This research demonstrated that considerable daily variation exists in the variety and amount of feeds offered to and consumed by cattle in these farming systems. Preferential feeding of adult female animals, the number of animals fed together, variation in the amounts of feed offered to the animals and consumed by them, variability in the composition of individual feeds, and competition between animals for feed are significant sources of variation in the diet. The highly variable nature of cattle diets make efforts to predict cattle performance very difficult. The fourth recommendation to farmers is for steps to be taken to remove one or more sources of variation in diet. Farmers may house each of their animals individually. Individual housing eliminates competition between animals for feed. Also, farmers tend to offer more feed to animals housed alone than to those fed in groups of two or more. Individual housing requires extra labor and the purchase of building materials on some farms since existing cattle pens must be rebuilt and augmented. Whether animals are housed individually or in groups, farmers may weigh feeds with a simple spring scale or measure feed volume to ensure that the amount of feed offered to each feeding group does not vary widely from day to day. Measuring feeds requires an increase in labor that may not be acceptable to some farmers. Farmers may adjust the size of their herds so that the number of animals does not exceed the available forage. This step may be met with resistance on many farms, since cattle are a species of cash savings as well as production animals. Finally, feeding extra concentrate supplements to cows in early lactation may be another means of supporting milk production. A cow in early lactation consuming 0.5 kg (FW) or more of concentrate daily may have a longer period of high milk production than a cow receiving no supplements.

The research described in this dissertation illustrates the importance of proper manure management to improve nutrient retention on smallholder farms in Kenya. Manure quality is closely linked to the quality of the cattle diet. The major sources of variation in cattle diets, which can lead to poor animal production and poor manure quality, are also demonstrated in this research. Cattle are valuable to smallholder

Kenyan farmers as a source of nutrients, income, and savings. Close attention to the management of cattle diet and manure will only serve to increase their contribution to the farmers' livelihoods.