# Quantifying the contribution of crop-livestock integration to African farming

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# Quantifying the contribution of crop-livestock integration to African farming

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*A mis hijos Robin e Ivan*

# Abstract

Smallholder farming systems in Sub-Saharan Africa are often nutrient-limited systems that depend largely on the use of land resources for their subsistence. Crop-livestock integration is an effective means by which nutrients can be rapidly recycled within and between farms. However, there is great uncertainty over which are the critical stages of nutrient transfer through crop-livestock systems. Each transfer of nutrients within the farming system provides a risk of inefficiency, which depends on the type of system, its management practices and site conditions. Because livestock fulfil several functions in crop-livestock systems, and farmers manage their animals according to the weight assigned to each function, there are trade-offs between increasing animal productivity, and income from livestock and sustaining crop production through cycling nutrients from animal manure. This thesis is a contribution to development of an analytical tool, the NUANCES framework, to support the analysis of trade-offs in crop-livestock systems, with focus on opportunities for intensification and maximisation of the benefits from crop-livestock integration for smallholder farmers. The framework that was developed can be used to analyse options for intensification at different scales, from the cattle sub-system, farm scale to village scale.

Efficient use of animal manures depends on improving manure handling and storage, and on synchrony of mineralisation with crop uptake. Model calculations with the HEAPSIM model show that manure management during collection and storage has a large effect on the efficiency of C and nutrient retention. Differences in nitrogen cycling efficiency (NCE) between farms of different wealth classes arise due to differences in resource endowment. Measures to improve manure handling and storage are generally easier to design and implement than measures to improve crop recovery of N. Covering manure heaps with a polythene film reduce mass and N losses considerably. For the poor to increase overall NCE, investment in cattle housing and recycling of urinary-N is required. Direct application of plant materials to soil results in more efficient cycling of N, with lower losses than from materials fed to livestock and the applying manure to the soil. However, livestock provide many other benefits highly valued by farmers.

Evaluation of lifetime productivity is a sensible strategy to target interventions to improve productivity of smallholder dairy systems. Model simulations with LIVSIM show that it is possible to maximise lifetime productivity by supplementing with concentrates to meet the nutritive requirements of cattle not only during lactation but also during early development to extend productive lifetime. Reducing mortality by implementing health care management programmes must be included in interventions to increase dairy outputs. Improving lifetime productivity has a larger impact on small-holders' income than interventions targeted to improving daily milk yields through feeding strategies.

Indicators of network analysis (NA) are useful to support discussions on diversified and sustainable agro-ecosystems and allow assessment of the effects of farm management strategies to improve the system design. The amounts of N cycled in crop-livestock systems in the highlands of East and southern Africa were small and comparable in size at all sites (less than 2.5 kg N *per capita* per year). Dependency on external inputs to sustain current production was larger for poor than for wealthier households, who had larger soil N storages per capita. Because increases in size of the network of N flows and organisation of the flows lead to increases in productivity and food self-sufficiency, combination of both strategies may improve not only productivity but also adaptability and reliability of smallholder crop-livestock systems.

An analysis of village scale interactions in a crop-livestock system of NE Zimbabwe using NUANCES-FARMSIM showed that the grasslands contribute to c. 75% of the annual feed intake of the herd of the village, and that the crop residues produced by the non-livestock owners sustained c. 30% of the intake of livestock during the critical dry season. The removal of carbon (0.3−0.4 t C $y^{-1}$) resulted in a long term reduction of the yields of their farms. Impeding the access of livestock to the crop residues of non-livestock owners increases the quality of their soils modestly and improved yields in the mid- to long term. Adding mineral fertiliser to the whole (community) system concurrently with changes to the current management of the crop residues and manures appears to be a promising strategy to boost the productivity of the community as a whole. There are benefits in terms of productivity and resource use efficiency of closer integration between crops and livestock. Opportunities seem to be small, but still may play an important role in rehabilitating soils together with other measures. However opportunities for intensification have to be explored in a broader context, taking into account that farmers face constraints at higher scales, constraints that need to be relaxed by proper policies and interventions.

**Keywords:** System analysis, modelling, smallholders, manure, diversity, feeding strategies, resource use efficiency, NUANCES

# Contents

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Chapter 1

# General introduction

# 1. Crop-livestock integration

Smallholders in Sub-Saharan Africa (SSA) depend largely on the use of land resources for their subsistence. They are exposed to a variety of risks, including harvest failure due to the effects of climate change, policy shocks, labour shortage and death and illness of livestock (Dercon, 2002). Farmers believe that income generated outside of cropping is crucial to their livelihoods and recognise livestock, and low dependency on external inputs as factors decreasing vulnerability to risk (Block and Webb, 2001). Buying and selling cattle is a common strategy for coping with risk but a large proportion of smallholders in Sub-Saharan Africa does not own livestock. Livestock has multiple purposes in smallholder systems. It provides food and income, draught power for crop production, manure to improve soil fertility and it is a key asset for insurance in times of scarcity. Depending on the importance assigned to these functions, farmers manage livestock in different ways to suit specific purposes.

Dixon et al. (2001) identified five major strategies for the improvement of farm household livelihoods: (i) expansion of the cropland or herd size, (ii) diversification, (iii) intensification of production systems, (iv) increase of off-farm income (both agricultural and non-agricultural), and (v) complete exit from the agricultural sector. Farmers' vulnerability to risks is increased where there is not much scope for further agricultural expansion. Diversification is a risk management strategy, which from a natural resource perspective may enable the realisation of complementarities between different production activities, such as between crops and livestock. Intensification and crop-livestock integration are usually consequences of the increased population pressure for land (McIntire et al., 1992).

Diversity and integration are often associated with sustainable and resource use efficient systems (Dalsgaard and Oficial, 1997), but diverse farm household systems are not necessarily integrated. For example, multiple activities may be undertaken within farm households without having real connectivity. In contrast, integration occurs when the farming activities are interdependent. In an integrated and diverse farming system, its compartments may be connected in several different ways so that the degree of integration also varies. In crop-livestock mixed systems, intensification may occur through the introduction of animal traction, use of animal manure, fodder production, stall feeding and replacement of animals. Intensification creates opportunities for increasing integration due to increased production of crop residues that may be fed to livestock, and manure that may be used for cropping. But does crop-livestock integration lead to increased resource use efficiencies and higher productivity of the farming system?

## 1.2 The role of livestock in crop-livestock systems

In a line of intensification following population pressure, mixed systems move from obtaining almost exclusively the feed for livestock from grasslands, at one extreme, to the other in which feeds are produced on-farm or are imported. Fernández-Rivera and Schlecht (2002) proposed the use of the inverted U-shaped curve of McIntire et al. (1992) to explain the sources used to manage soil fertility in mixed systems following that line of intensification, going from fallows when there is no integration between crops and livestock, passing through various degrees of integration with the use of crop residues as feed, producing fodder on farm, to finally specialise and import the feeds for cattle and the fertilisers for cropping (Fig. 1A). Baltenweck et al. (2004) indicated that the characterisation of intensification of McIntire et al. (1992) does not account for agro-ecological potential and labour opportunity costs. These authors proposed four drivers of intensification: education, labour opportunities, market access and costs of labour and land. The study of Baltenweck et al. (2004) in 48 sites across three continents showed that the ratio of cost of labour to cost of land, the proximity to markets and the ability of farmers to understand the benefits of introduction of new technologies explained largely the level of intensification in crop-livestock systems measured through the feeding system and use of manures in cropland. In marginal areas, where risks to agricultural production are high, the transition to more intensified forms of mixed farming may be prevented by outmigration. In contrast, in higher potential areas the transition to specialised systems may be prevented by the preference of farmers to produce a large share of their staple food (Romney et al., 2004).

It is often stated that crop-livestock integration is an effective means by which plant nutrients can be rapidly recycled within and between farms (Thornton and Herrero, 2001). However, there is great uncertainty on the critical stages of nutrient transfer through crop-livestock systems. There is potential for increasing livestock productivity through better feeding management, which may require increased labour allocation to livestock activities, and compete with other farm activities. Improving cattle stalls and manure collection methods requires investment by farmers, investment that needs to be justified by the benefits in terms of crop production or stability of crop yields. Livestock produce physical products but also play an important role as accumulation of wealth, insurance and display of status (Moll, 2005). This function is especially important where it is not fulfilled by other means (Slingerland, 2000). The financing role may bring negative consequences for crop production because sale of animals prevents benefits from the manure and animal traction for crops. Because livestock fulfil several functions in crop-livestock systems, and farmers manage their animals according to the weight assigned to each function, there are trade-offs between increasing animal productivity, and income from livestock and sustaining crop production through cycling nutrients from animal manure.

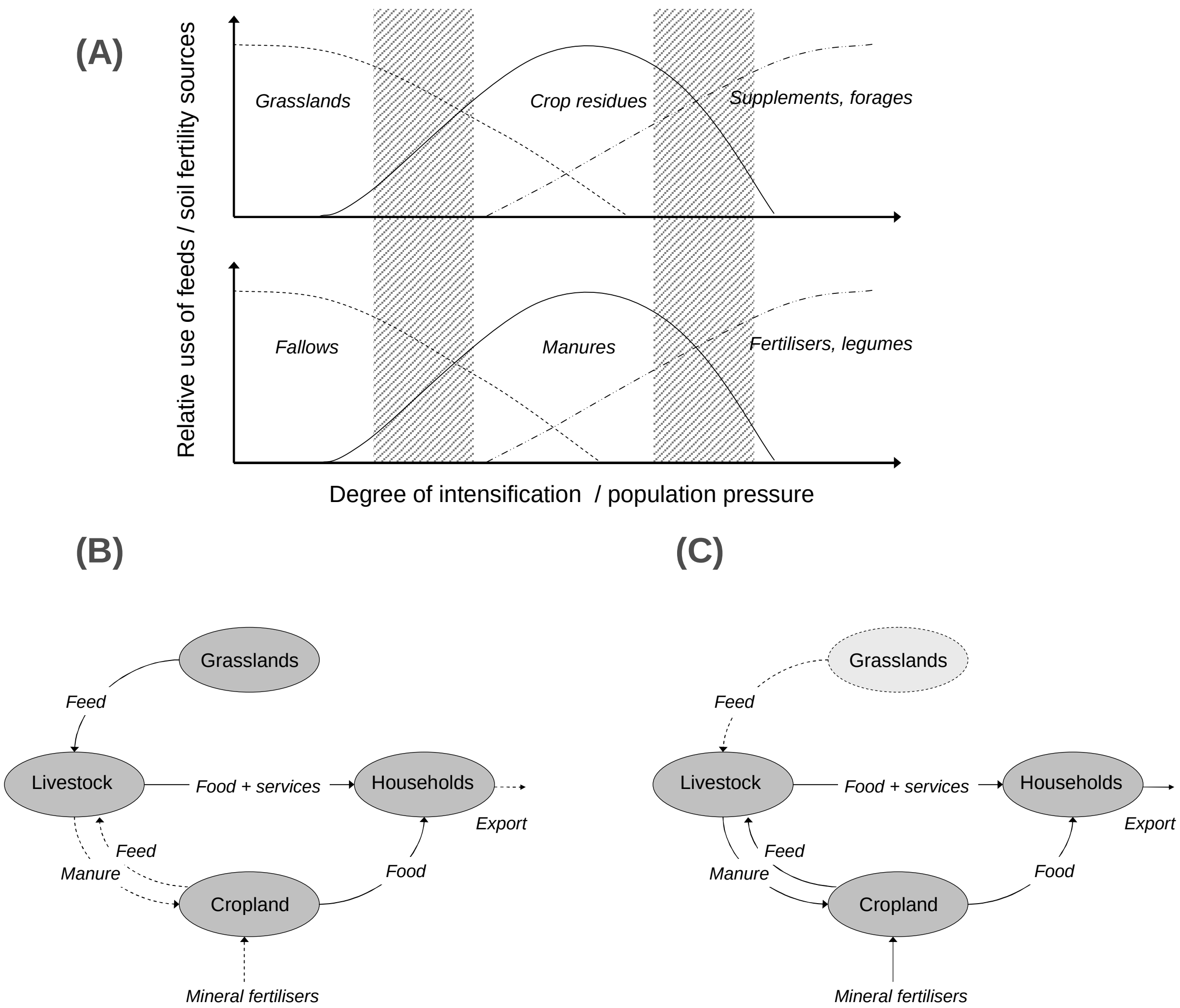


Figure 1: (A) The relative importance of feed resources and soil nutrient sources for crop production in mixed crop-livestock systems following a line of intensification and population pressure. Source: Fernández-Rivera and Schlecht (2002). (B) Schematic representation of a crop-livestock system at a relatively low level of intensification, where most feeds come from grasslands. The main feedbacks among the system compartments are shown. (C) Crop-livestock system at a high degree of intensification, where most feed is produced in cropland.

## 1.3 Crop-livestock integration and nutrient cycling

Powell et al. (1996) stated that nutrient recycling is critical to maintain the productivity of the land and to maximise the benefits from nutrient inputs in most African farming systems. Nutrients in mixed crop-livestock systems are cycled through several steps, and losses at each step may decrease the amount of useful output. A measure of nutrient cycling and a measure of the dependency on external inputs for production are needed to evaluate resource use efficiencies and vulnerability of farming systems. Increasing soil organic matter may serve both restoration of soils and mitigation of the effects of climate change through reduced vulnerability to erratic rainfall. According to Vagen et al. (2005) opportunities for soil organic carbon (SOC) sequestration in SSA are: (i) conversion of traditional cultivation into no-till or using a combination of animal manure and fertilisers, (ii) improved fallows (mixed and natural). These technologies need to be evaluated in crop-livestock systems at a relevant scale, because their benefit may not be perceived by farmers if they do not fit the farm livelihood due to constraints at an immediate lower or higher scale.

## 1.4 Integration and scales

The crop-livestock integration concept is often reduced to mixed farming aimed at arable farmers with the objective of increasing crop production to feed the increasing population (Slingerland, 2000). Exchange of crop residues and manure between specialised farm systems appears promising since nutrient recycling takes place. Integration may potentially benefit different farmers within a farming community. López-Ridaura (2005) in a scenario analysis of households' conflicting objectives (food self-sufficiency, forage self-sufficiency and value of the agricultural production), found that the wealthier farmers with large herds produce only part of the feed needed and profit the most from communal grazing resources. In this case, there is competition among farmers for limited organic resources which are often crucial to sustain soil productivity. At the village scale, 'islands of fertility' or 'hot spots' are created where good yields are obtained (Breman et al., 2008), but with an uneven distribution among different farmers in the community (Ramisch, 2005). There are other (social) mechanisms that (at least partly) compensate for the nutrient losses and lower yields of a proportion of the farmers in a community (Fairhead and Leach, 2005). These mechanisms include for example exchanges of oxen between livestock owners and non-livestock owners, food-for-work, and manure exchanges.

It is often argued that the poorest smallholders would benefit the most from integrating livestock with crops because of the reduction of vulnerability to risk (through the insurance function of livestock), and because of the opportunities created for recycling and maintaining soil productivity. Assessments are needed of how well different strategies fit within the farm livelihoods in smallholder farming systems. These analyses are conducted under the Nutrient Use in ANimal and Cropping systems – Efficiencies and Scales (NUANCES) framework (see www.africanuances.nl) (Giller et al., 2006).

The key objectives of AfricaNUANCES were: (i) to understand spatial and temporal dynamics of rural livelihoods and their relationship with food security, sustainability, and resilience of natural resource base, (ii) to explain farmers' decisions regarding resource allocation across heterogeneous farms and analyse inefficiencies, and (iii) to identify measures to promote successful and sustainable agricultural development. This thesis is a contribution to the development of the analytical tools to support the analysis of trade-offs in crop-livestock systems, with focus on opportunities for intensification and maximising the benefit from crop-livestock integration.

## 2. Objectives

The main objective of this research was to quantify the contribution of crop-livestock integration to smallholders' livelihoods in terms of productivity, and the perspectives for the sustainability of crop-livestock mixed farming systems.

Specific objectives

1. To develop analytical tools to analyse crop-livestock interactions at different scales, from livestock sub-system, farm scale, to village or community scale.
2. To identify opportunities for interventions through exploring current and alternative management options in crop-livestock mixed systems.
3. To understand the dynamics of crop-livestock interactions and identify opportunities for increasing resource use efficiency at farm and village scale.

## 3. Methodology

A combination of qualitative and quantitative system analytical methods was used to address the main objective. In order to analyse crop-livestock interactions (McIntire et al., 1992), scales and system boundaries need to be clearly defined. Farm household activities are conceptualised as compartment of the system. A compartment is associated to a state (e.g. storage of nutrients) which may receive inputs and donate outputs to the environment. Within the system, flows pass from one compartment to another. The conceptualisation of compartments within systems enables to work at different scales. The compartments of the farm household system were defined as related to activities and certain criteria. Scaling up, the farming systems consist of farm households that are represented as compartments. Scaling down, at farm level, compartments may represent different farming activities.

The NUANCES framework combines participatory research, farm typologies, data-mining, experiments and modelling tools to identify opportunities for intensification of smallholder systems in Sub-Saharan Africa. Different steps in the methodology are articulated using the 'DEED' approach:

1. **D**escribe, current production systems and their problems;
2. **E**xplain, current farmers' decisions on resource allocation and their consequences;
3. **E**xplore, options for agro-technological improvement for a range of possible future scenarios;
4. **D**esign, new management systems that contribute to the sustainable intensification of smallholder agriculture.

Throughout this thesis, examples of different mixed crop-livestock system are chosen to study crop-livestock interactions and opportunities for intensification. Different aggregation and temporal scales are used depending on the problem definition, and a combination of methods is used to characterise each case study. Modelling was used to explore options, at the scale of interest, by asking 'what if' questions (Van Ittersum et al., 1998). On the one hand, the modelling approach used involves a relatively large level of uncertainty, due to for example our incapability to predict farmers' decision making and adaptive management in relation to drivers of change (e.g. policies, markets, climate). On the other hand, the models were used to summarise existing knowledge, and therefore as far as it was possible, and data was available for parameterisation and tests, a high level of causality was included to describe biophysical processes.

The tools developed and used throughout this thesis attempted to comply with the minimum requirements to modelling properly crop-livestock systems listed by Thornton and Herrero (2001): (i) Describe and quantify the interactions between components, (ii) Represent management, (iii) Determine the impact of management strategies on land and resource use, (iv) Quantify nutrients balances at whole-system level, (v) Quantify system's performance variability associated with weather, (vi) Allow trade-off analysis and both medium and long term analyses of strategies, (vii) Use minimum data sets for parameterisation, tests and general use, and (viii) Integrate data from different levels of aggregation. Because of the complexity in the crop-livestock systems analysed, compartments were treated in a descriptive rather than in a mechanistic fashion. Information available was summarised, making use of empirical models and rule-based methods to describe management.

The crop-livestock systems chosen for the analyses show contrast in degree of intensification, the main sources of feed, the soil fertility management practices, and agro-ecological potential (Table 1). In the mixed systems of the communal farming areas of Zimbabwe, maize is the most important crop, mainly cultivated for self-consumption although surpluses are marketed. Livestock feed during the rainy season on communal grasslands and on crop residues during the dry season (Fig. 1B). The production goals for the livestock sub-system are animal traction and manure for crop production, milk is considered a by-product. At least half of the excreta are left in the land where livestock graze, while the rest may be recycled on-farm for crop production. Because of the production goals, and the other roles of cattle, farmers aim at increasing herd size. The highlands of northern Ethiopia were used as another case study. The main difference with the site at Zimbabwe are the lower rainfall and the higher reliance of livestock on communal grazing, and that due to altitude, farmers grow temperate cereals instead of maize.

Table 1: Main characteristics of the farming systems used as case study in this thesis.

| | Ethiopia | Zimbabwe | Kenya |
|---|---|---|---|
| Study sites | Tigray | Murewa | Central and western |
| Rainfall (mm) | 540 (270−810) (unimodal) | 750−1000 (unimodal) | 1400−2000 (bimodal) |
| Main crops | barley, wheat, field peas, faba beans, buckwheat, teff and prickly pears | maize, groundnut, sorghum, soybean, cowpea | maize, beans, potatoes, cassava, sweet potatoes, yams, banana, coffee, tea, |
| Livestock | Free ranging in communal grasslands; Zebu cattle (mainly Boran), goats, donkeys and mules and chicken | Free ranging in communal grasslands; Zebu cattle (Mashona and Africander), goats, and chicken | Stalled or tethered on farm (cut and carry); Zebu cattle (mainly Boran), and crossbred, goats, sheep, chicken |
| Soils | Leptosols, Luvisols and Cambisols | Lixisols and Luvisols | Nitosols, Ferrasols and Acrisols |
| Farm size (ha) | 0.3−2.5 | 0.5−3.0 | 0.5 – 4.0 |
| Population density (inhabitants km$^{-2}$) | ~130 | ~100 | 650−700 |

In the crop-livestock systems of the highlands of Central and western Kenya, dairy systems are used as examples. Here the main sources of feeds are forages produced on-farm or purchased from the market, and dairy concentrates used as supplements. Grasslands are virtually absent or contribute little to total feed intake. Dairy cattle are normally stalled and fed *in situ* (zero-grazing), where feed availability and feed quality are controlled by the farmer. The feed refusals together with the animal manure are used to produce compost that is applied to the crops. Manure and fertilisers are used in combination in the cropland (Fig. 1C).

## 4. Outline of the thesis

In Chapter 2 we identify the critical steps where the efficiency of nitrogen (N) cycling through livestock in African smallholder crop-livestock farming systems could be increased. In Chapter 3, we describe a simple model to analyse the effect of manure management on the efficiency of mass and nutrient retention. This model was built with information collected on-farm on manure excreted and manure management and derived from experimental results and literature to analyse losses during manure storage. The model was used to analyse N cycling efficiency within smallholder farms in western Kenya. In Chapter 4, a dynamic modelling approach was used to explore the effect of feeding strategies and mortality on the lifetime productivity of dairy cattle, and to identify points where interventions may have a productive impact. We used as an example the farming systems of the highlands of Central Kenya. In Chapter 5 we introduce a method based on Network Analysis (NA) to characterise and assess the diversity and integration in farm household systems. The indicators are discussed in an application to mixed crop-livestock systems of the highlands of Northern Ethiopia where we used nitrogen (N) flows to illustrate the utility of the method. In Chapter 6 we study the size, integration, diversity and organisation of N flows and cycling within contrasting crop-livestock systems of the highlands of northern Ethiopia, western Kenya and NE Zimbabwe. Here we relate the indicators of NA to systems performance, assessed through biomass production, N conversion efficiency and household food self-sufficiency. In Chapter 7 we explored the impact of interactions at the community level on the productivity of different farm types in mixed crop-livestock system of NE Zimbabwe. We focused on the interactions due to collective management of feed resources, under current and alternative management practices. In this chapter, we combined information available for the area of study, and used the NUANCES-FARMSIM modelling framework, imposing a number of scenarios to represent current and alternative practices. In Chapter 8, we put in perspective the main findings and limitations encountered during the course of this research and a discussion on future research is elaborated.

Chapter 2

# Nitrogen cycling efficiencies through resource-poor African crop-livestock systems†

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## Abstract

Success in long-term agricultural production in resource-poor farming systems relies on the efficiency with which nutrients are conserved and recycled. Each transfer of nutrients across the farming system provides a risk of inefficiency, and how much is lost at each step depends on the type of farming system, its management practices and site conditions. The aim of this review was to identify critical steps where efficiency of nitrogen (N) cycling through livestock in smallholder crop-livestock farming systems could be increased, with special emphasis on Africa. Farming systems were conceptualised in four sub-systems through which nutrient transfer takes place: 1. Livestock: animals partition dietary intake into growth and milk production, faeces and urine; 2. Manure collection and handling: housing and management determine what proportion of the animal excreta may be collected; 3. Manure storage: manure can be composted with or without addition of plant materials; 4. Soil and crop conversion: a proportion of the N in organic materials applied to soil becomes available, part of which is taken up by plants, of which a further proportion is partitioned into grain N. An exhaustive literature review showed that partial efficiencies have been much more commonly calculated for the first and last steps than for manure handling and storage. Partial N cycling efficiencies were calculated for every sub-system as the ratio of nutrient output to nutrient input. Estimates of partial N cycling efficiency (NCE) for each sub-system ranged from 46–121% (Livestock), 6–99% (Manure handling), 37–85% (Manure storage) and 3–76% (Soil and crop conversion). Overall N cycling efficiency is the product of the partial efficiencies at each of the steps through which N passes. Direct application of plant materials to soil results in more efficient cycling of N, with fewer losses than from materials fed to livestock. However, livestock provide many other benefits highly valued by farmers, and animal manures can contain large amounts of available N which increases the immediate crop response. Manures also can contribute to increase (or at least maintain) the soil organic C pool but more quantitative information is needed to assess the actual benefits. Making most efficient use of animal manures depends critically on improving manure handling and storage, and on synchrony of mineralisation with crop uptake. Measures to improve manure handling and storage are generally easier to design and implement than measures to improve crop recovery of N, and should receive much greater attention if overall system NCE is to be improved.


**Keywords:** Cattle, compost, feed intake, manure, partitioning, nitrogen use efficiency, N losses

# 1. Introduction

Extensive areas in Africa have soils that are poor in organic matter, nitrogen (N) and phosphorus (P), where nutrient recycling is critical to maintain the productivity of the land (Powell et al., 1996) and maximise the benefits from nutrient inputs. Nutrients in mixed livestock-cropping systems are cycled in several stages, and losses at each stage may decrease the amount of useful output. Nutrient cycling efficiency (NCE) is defined as the ratio of effective or useful output to input in any system or system component, provided that the output may be re-used within the system, e.g. kg manure N per kg feed N. For this review of nutrient cycling through livestock, a farming system was conceptualised as consisting of sub-systems through which nutrient transfer takes place: 1. Livestock; 2. Excreta collection and handling; 3. Manure storage; and 4. Soil availability, crop capture and conversion to harvested products (Fig. 1).

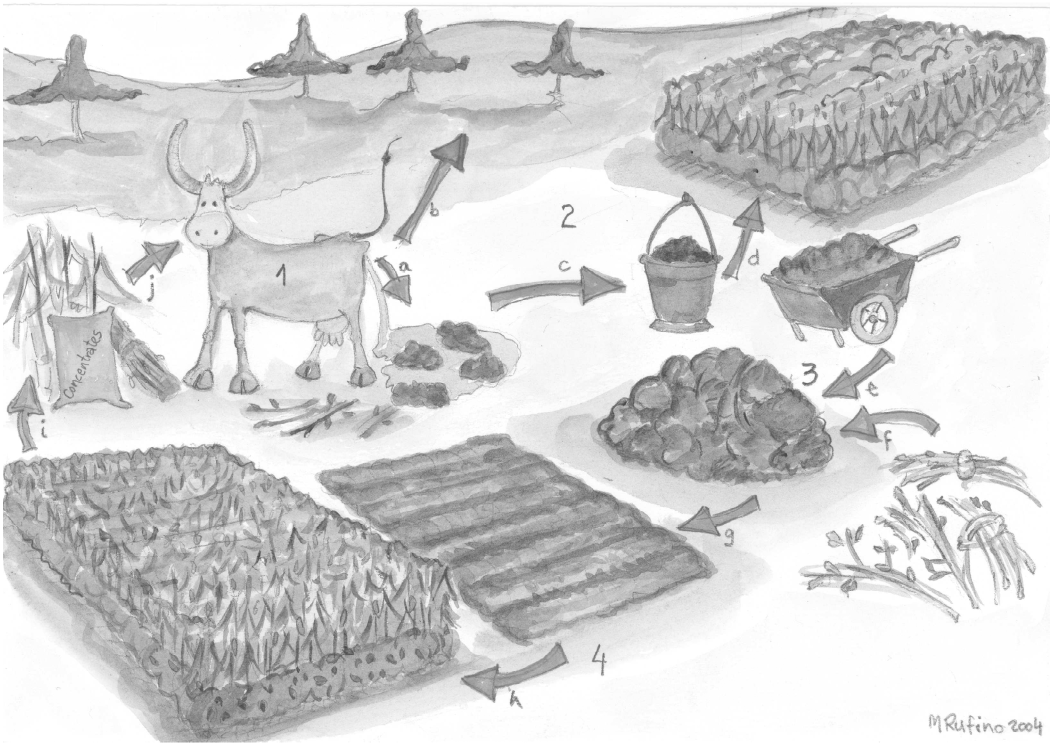


Figure 1: Nitrogen transfer among sub-systems across the farming system: 1. Livestock: a certain amount of dietary N is consumed by livestock. Excreta may be left in the stalls (flow a) and/or on rangelands (flow b) depending on livestock management. 2. Manure collection and handling: manure is collected (flow c) and applied directly to croplands (flow d) or composted (flow e). 3. Manure storage: plant materials may be added to excreta (flow f) before composting. 4. Soil availability, Crop capture and conversion: manure or compost is applied to croplands (flow g) and a proportion of the N contained may become available. Crop plants take up a proportion of this available N (flow h), and the N taken up is partitioned by the plant into grain N and plant residues (flow i). Crop residues may be returned to livestock (flow j).

Overall system efficiency can be calculated as the product of the partial efficiencies at each stage through which the N passes. Interactions between the partial efficiency terms may occur; for example diet quality may affect not only the proportion of consumed N excreted, but also the proportion of excreted N which can be collected. Such interactions cannot be included in an efficiency analysis unless a dynamic modelling approach is taken, and have therefore been ignored in the current study for the purpose of simplicity.

The different pathways that plant materials can follow may result in a different overall nutrient cycling efficiency (Fig. 2). Plant materials such as crop residues or green manure may be used directly or after composting as nutrient inputs that will, after decomposition, be taken up by crops to produce biomass and grain. Alternatively, farmers may decide to feed plant materials to livestock. The passage of low quality feed through the rumen decreases the quantity of organic material for soil amendment, but generally increases the nutrient concentration. Livestock represent a means of gathering nutrients from the surroundings while grazing on communal land, which can become additions to the farm when manure is deposited during confinement. Livestock may also affect nutrient redistribution within farming communities, by grazing on crop residues and thus removing nutrients from the fields of farmers without livestock. The integration of livestock offers the opportunity to increase the cycling of nutrients within the farming system, though it also increases the risk of nutrient losses. Effects of livestock on nutrient cycling must be considered in relation to other cultural and economic reasons for owning them. The benefits of the integration of livestock into farming systems and particularly the long-term consequences of transferring nutrients from rangelands to croplands are still actively debated (De Ridder and Van Keulen, 1990; Turner, 1995; Sumberg, 2003; De Ridder et al., 2004).

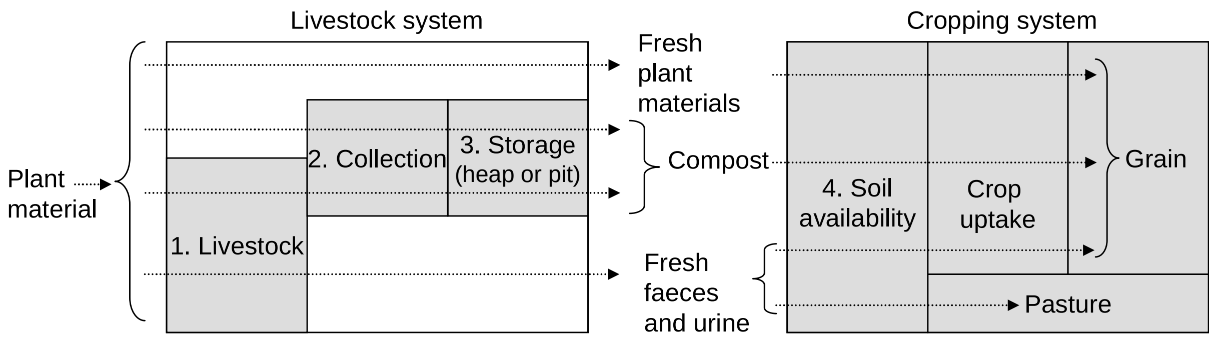


Figure 2: Pathways that nitrogen contained in the plant material can follow before being converted into grain N. Numbers identify the sub-systems for which nitrogen use efficiency was calculated in this review.

The review focuses on nitrogen (N) cycling efficiency (NCE). Nitrogen is the most limiting nutrient for production in most agricultural systems, due to the large amounts harvested with the crops and because it can easily be lost through gaseous losses, leaching, runoff or erosion. N and P are the most studied elements in flows and balances of nutrients in agricultural systems (Smaling et al., 1999), and the amount of published data enables calculations on N cycling efficiency to be made for diverse environments. Other nutrients are discussed since their availability may influence NCE.

Cattle and sheep are the most numerous ruminants in the world occurring mainly in the tropics and developing countries (Van Soest, 1994). This review focuses on cattle, since these are the most important livestock in most farming systems in terms of abundance and amounts of nutrients transferred. Cattle are important assets for smallholder farmers that can easily be converted into cash when required. Bebe et al. (2003a) found that farmers in the highlands of Kenya mainly keep cattle for milk production, for family subsistence or to generate cash income. Manure was perceived as a non-marketable product that contributes to crop production but was not a priority when addressing management. In some African farming systems, manure production is a major reason indicated by smallholder farmers for keeping cattle (Baijukya et al., 2005), whereas in other systems, such as arid areas of Zimbabwe, manure is a potential resource for nutrient recycling that is hardly used (Mapfumo and Giller, 2001).

Livestock management varies between agroecological regions as a result of the variability in available resources and human population pressure, which determine the land available for cropping and grazing activities (Table 1). As pressure on land increases, the proportion cultivated increases relative to grazing land, and there is a trend towards more intensive livestock husbandry (Stuth et al., 1995; Roothaert and Paterson, 1997). Less densely populated areas generally have extensive common lands on which livestock are herded. With increasing population density, herds are confined to smaller grazing areas during the rainy season to avoid crop damage. This may result in animals' undernourishment being shifted from the dry season to the wet season, and higher risks of pasture overgrazing (Powell et al., 1996). More intensive grazing close to villages during the wet season can lead to the dominance of unpalatable or poorly-productive, short cycle species in rangelands. This can reduce livestock production and therefore reduce nutrient transfers to croplands, which in turn can diminish crop residue availability for livestock. As population density increases still further, and particularly in areas with good access to urban markets, zero-grazing with improved dairy cattle and cultivated fodder becomes the predominant form of management.

Table 1: Livestock production systems in Sub-Saharan Africa (adapted from Sere and Steinfeld, 1996 and Thornton et al., 2002).

| | Stocking rates (TLU km$^{-2}$) | Livestock system | Description | Total land area (km$^2$) | Total area (%) | Countries |
|---|---|---|---|---|---|---|
| Rangeland-based systems<br>Livestock only: More than 90% of the feed comes from rangelands, pastures, annual forages and purchased feeds and less than 10% from crops. | 5-10 | Temperate/tropical highlands (LGT)<br>Constrained by low temperatures | Cattle and sheep extensive production mainly with local breeds for local markets and subsistence. Potential production is relatively low. | 210,054 | 1 | Ethiopia, South Africa |
| | 1-5 | Humid/subhumid (LGH)<br>Growing season > 180 days | Agropastoralism and ranching systems in West and Central Africa. Cattle are the dominant species, being the production market oriented. Sheep and goats are only kept for local consumption. | 2,454,870 | 10 | Angola, Benin, Cameroon, Central African Republic, Congo, Côte d'Ivoire, Guinea, Nigeria, Sudan |
| | 0-5 | Arid/semiarid (LGA)<br>Growing season < 180 days | Pastoralist in the Sahel Northern Kenya, Southern Sudan, Southern Ethiopia. Sheep and goats, few cattle or camels. Very low crop-livestock intensification. Herds move across diverse landscapes. | 6,300,755 | 26 | Angola, Botswana, Chad, Ethiopia, Kenya, Madagascar, Mali, Mauritania, Mozambique, Namibia, Niger, Somalia, South Africa, Sudan, Zambia |
| Mixed farming systems<br>(Rainfed)<br>More than 10% of feed comes from crop by-products or more than 10% percent of the total value of production comes from non-livestock farming activities. | 35-55 | Temperate/tropical highlands (MRT)<br>Constrained by low temperatures | Smallholders in the East African mainly small scale dairy farms. Multipurpose cattle (meat, milk and traction). | 793,957 | 3 | Burundi, Ethiopia, Kenya, Rwanda, Tanzania Uganda |
| | 5-20 | Humid/subhumid (MRH)<br>Growing season > 180 days | Tsetse belt across Central and West Africa. Local breeds are widely used. Livestock have multiple roles, particularly traction and manure. | 2,328,326 | 10 | Cameroon, Congo, Côte d'Ivoire, Ghana, Nigeria |
| | 10-20 | Arid/semiarid (MRA)<br>Growing season < 180 days | Mixed crop-livestock farms in the Sahel, semi-subsistence mixed communal sector in Zimbabwe, dairy farms in Senegal and Mali. Livestock represent an asset to farmers. Land that is not suitable for cropping is owned by the community and used for grazing. | 3,410,903 | 14 | Botswana, Burkina Faso, Chad, Kenya, Mali, Mozambique, Niger, Nigeria, South Africa, Sudan, Tanzania, Zambia, Zimbabwe |
| Mixed farming systems<br>(Irrigated)<br>These are similar to the previous systems, but more than 10% of the value of non-livestock farm produce comes from irrigated land use. These systems are very rare in Africa. | >20 | Temperate/tropical highlands (MIT) | It is found in regions of high population density. | 9931 | <1 | Ethiopia, South Africa |
| | >20 | Humid/subhumid (MIH) | Cattle are mainly tethered or fed cut-and carry forages. | 817 | <1 | Ethiopia |
| | >20 | Arid/semiarid (MIA) | Sheep and goats consume crop residues. | 109,906 | <1 | South Africa, Sudan |

Since fodder availability is very site- and season-specific, in this review we have not attempted to estimate the efficiency of intake of N in fodder; instead we define the system as beginning with ingested forage. Nitrogen contained in ingested forage is used to build animal protein or excreted in faeces and urine. In ruminant nutrition, a high ratio of animal protein formed in milk and meat to N intake is defined as an efficient use of N. These animal products can be used to generate income or improve human diets, but generally remove nutrients from the farming system. Only the remainder of the N which is partitioned to excreta can be recycled within the production system if collected and used. Depending on the quality of the feed, excreted N is partitioned differentially between faeces and urine, which has a large effect on the efficiency of collection of excreta N. Assuming that the main production goal is animal protein, then to maximise N recycling within the farming system partitioning of excreta N into faeces N should be as high as possible.

Cattle excreta may be left in the rangelands or croplands where the animals graze, or collected. Losses during collection and handling of excreta are common. Urine cannot be collected from grazing animals, and is often physically lost from stalls. Fresh faeces are generally referred to as manure. Manure stored alone or mixed with urine, feed refusals or other organic materials is called compost after it has undergone a process of combined decomposition known as maturation or composting. Nutrient losses occur during composting, through leaching or volatilisation.

When composted or fresh excreta or plant materials are applied to soil, a proportion of the N these contain becomes available for plant uptake, through mineralisation of organic N or from mineral N already present (mineralisation efficiency). A proportion of this available N is actually taken up by crop or pasture plants (capture efficiency), and a proportion of this uptake is converted into useful plant products such as grain or forage (conversion efficiency). These three partial efficiencies may be treated separately (e.g. Van Noordwijk and De Willigen, 1986), but different studies have reported measurements using a range of different sub-system boundary definitions and so here they have been grouped together. Plant products are the final stage in the system considered. Considerations of nutrient return from human wastes, or from sale of products and purchase of nutrient resources, are beyond the scope of this review.

This review uses a systematic and analytical approach to estimate overall N cycling efficiency and to identify key sources of inefficiency in N cycling, through a review of studies which focus individually on discrete parts of crop and livestock systems. Our objective was to identify critical steps where efficiency of N cycling in smallholder crop-livestock farming systems could be increased, with special emphasis on Sub-Saharan Africa.

## 2. Methods

The definition of system NCE as the product of partial NCEs at each of four N transfer steps was used as framework for a review on literature intensity for each of the identified sub-systems. Partial NCE can be calculated for every sub-system as the ratio of useful nutrient output to nutrient input. Nitrogen partitioned to animal products (meat and milk) is not considered because this is usually removed from the system through sale or consumption and not further recycled. For the livestock sub-system, partial NCE is calculated as the amount of N in excreta as a proportion of N intake:

$$NCE_{livestock} = \frac{N\ excreted}{N\ intake}$$

True digestibility is the balance between feed intake and the residues that escape digestion. In studies where excreta N and N intake have both been measured, $NCE_{livestock}$ can be simply calculated as:

$$NCE_{livestock} = \frac{(Faecal\ N + urinary - N)}{N\ intake}$$

Another possibility is to calculate $NCE_{livestock}$ as:

$$NCE_{livestock} = \frac{(N\ intake - milk\ N - liveweight\ gain\ N)}{N\ intake}$$

However, N intake is often estimated indirectly from measurements of faecal N and of feed N digestibility *in vitro* or *in vivo*. *In vivo* measurements include microbial and endogenous matter, and thus reflect the apparent digestibility i.e. the balance between feed intake and total faeces production. Methods for estimating digestibility *in vitro* are more related to true digestibility (Van Soest, 1994). Studies where intake was estimated indirectly were not used to calculate $NCE_{livestock}$, because this would simply reflect the assumed ratio between inputs and outputs. Some studies of this kind are discussed in relation to N partitioning between faeces and urine. In economic terms, depending on the goals of the livestock farmers, minimising $NCE_{livestock}$ and ensuring maximum use of N in protein production would be preferable.

Partial NCE during the collection and handling step is calculated as the amount of N in collected excreta as a proportion of the amount excreted:

$$NCE_{collection} = \frac{N\ collected}{N\ excreted}$$

During the storage step, partial NCE is calculated as the amount of N in compost as a proportion of the N contained in the fresh materials composted:

$$NCE_{storage} = \frac{N\ in\ applied\ manure}{N\ collected}$$

For the soil and crop sub-system, partial NCE is the amount of N in the harvestable plant product as a proportion of the amount of N applied to the soil:

$$NCE_{soil\&crop} = \frac{N\ in\ grain}{N\ in\ applied\ manure}$$

Because $NCE_{soil\&crop}$ is the product of N uptake efficiency and N conversion efficiency, we calculate those efficiencies separately as:

$$N\ uptake\ efficiency = \frac{Biomass\ N}{N\ in\ applied\ manure} \quad \text{and,}$$

$$N\ conversion\ efficiency = \frac{N\ in\ grain}{Biomass\ N}$$

The contribution of manure to build up of soil organic carbon (SOC), and total soil C stocks, is considered to be an important extra benefit of using manure as a soil amendment. Long-term experiments indicate that additions of 5−10 t $ha^{-1}$ $y^{-1}$ of manure are sufficient to maintain SOC close to the contents of the soil under undisturbed savanna vegetation in West Africa (Agbenin and Goladi, 1997; De Rouw and Rajot, 2004; Mando et al., 2005). In an experiment in Saria, Burkina Faso, additions of 2 t C $ha^{-1}$ $y^{-1}$ to plots cropped to sorghum (*Sorghum bicolor* L.) and hand-hoed over a 10 year period resulted in a net increase of approximately 3.5 t C $ha^{-1}$ to the SOC pool (Mando et al., 2005). When tillage was done with oxen, the addition of SOC was not significant. This clearly shows that more information is needed to assess the role of manure in SOC build-up in a quantitative manner.

The overall N cycling efficiency is the product of partial efficiencies in all considered sub-systems:

$$NCE_{overal} = NCE_{livestock} \times NCR_{collection} \times NCE_{storage} \times NCE_{soil\&crop}$$

A potential flaw in this approach, common with similar exercises that look at series of efficiency factors, is that it may not be possible to equate the sum of the sub-system effects to the overall effect, because the sub-systems are not independent of each other and may interact in a non-linear fashion. Choosing any one value for efficiency of N flow through a sub-system, will unavoidably constrain the other efficiencies. Such effects have been ignored in our current study as model simulations of the whole system, which are not possible given our current knowledge, would be necessary to examine them.

The AGRICOLA (1970–2004), Biological abstracts (1969–2004) and CAB Abstracts (1972–2004) and Science Direct databases were used to identify sources of information. Keywords for the search were combinations of: cattle manure, Africa, manure, nitrogen, milk yields, dairy cattle, N availability, manure storage, manure decomposition and crop yields. The results of these searches were grouped into studies done in Africa and studies in high-input farming systems. Articles containing information on cattle management were considered to belong to the category of manure handling, since these may be used to derive excreta deposition in rangelands and kraals/bomas. Those African studies where partial NCE could be quantified are discussed.

# 3. Results

### 3.1 Research effort into different nutrient transfer stages

Publications on organic matter transfer and utilisation mainly deal with the livestock and soil-crop sub-systems, and there is a distinct lack of information regarding manure handling and storage (Fig. 3). Most of the studies reviewed did not quantify nutrient mass balances, and were not useful for our purpose. The sub-systems have all been studied more intensively in high-input systems, mainly in Europe, USA, Canada, Australia, and New Zealand, than in low-input tropical systems. Studies on N recovery efficiency for cattle are abundant for high input farming systems. In the last few years these studies focused on the control of dietary N to reduce N emission from dairy production. In Africa, the aim of the researchers has been to increase milk yields and milk protein concentration, and most of the studies we found did not report partitioning of N into excreta. There has been little research on manure handling and manure storage in Africa. African studies of soil N mineralisation from manures comprise mainly laboratory incubations, with very few field experiments.

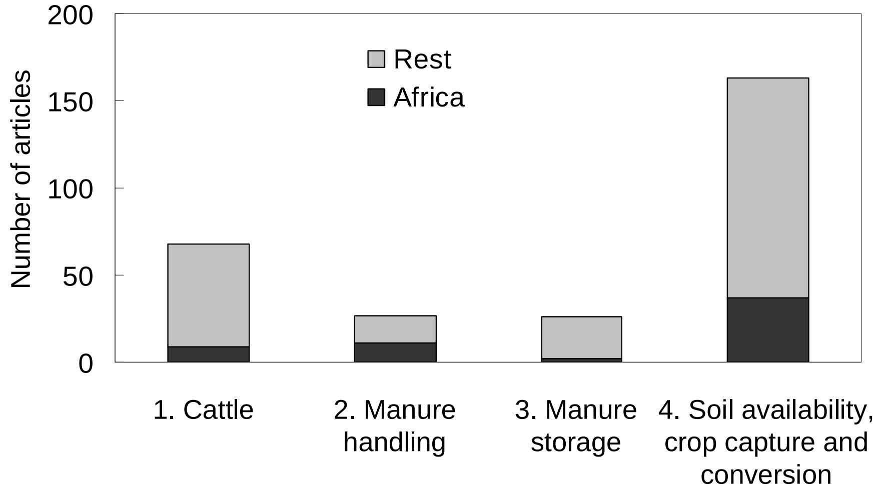


Figure 3: Numbers of articles describing studies of different stages of nutrient transfer through crop-livestock systems, from Africa and from other regions. Sources: AGRICOLA (1970–2004), Biological abstracts (1969–2004), CAB Abstracts (1972–2004) and Science Direct databases. Keywords: cattle manure, Africa, manure, nitrogen, milk yields, dairy cattle, N availability, manure storage, manure decomposition and crop yields.

In high-input systems these studies are mostly aimed at assessing the environmental impact of the manure spread on field crops. There are many more studies on crop N uptake than on crop N conversion, since the former comprise mainly greenhouse experiments where grain yield was not measured. Finally, there are many studies where N uptake in biomass is reported and grain yield were measured, but grain N content was not reported. African studies where quantification of partial NCE was possible represented only 8%, 7%, 5% and 8% of all publications on sub-systems 1–4, respectively.

### 3.2 Sub-system 1: Livestock

#### *3.2.1 Factors controlling feed degradation in the rumen*

Ruminants are able to make use of energy from cellulose because they maintain large populations of cellulose-degrading microorganisms in their rumens. Most cellulose is digested in the rumen, but a substantial portion of hemicellulose is fermented in the lower digestive tract (Van Soest, 1994). The nutritional value of cellulose depends largely on its degree of lignification, although there are other inhibitors and limiting factors such as silicification, cutinisation and intrinsic properties of the cellulose itself. The C:N ratio of organic materials is also a key factor, since rumen microorganisms require N for growth and efficient fermentation. Lignin is regarded as the most important fibre component that limits degradation and feed nutrient availability for cattle, because it protects cell wall structural polysaccharides from attack. Almost all ingested lignin can be recovered in the faeces (Chesson, 1997).

Analytical digestibility tests are based on sequential degradation with neutral and then acid detergent solutions (Van Soest, 1994). Neutral detergent solution leaves a fibre residue (NDF) containing lignin, cellulose and hemicellulose, with some protein and bound N, minerals and cuticular material. An acid solution of quaternary detergents leaves a fibre residue (ADF) containing lignin and cellulose. ADF also contains a little N, but this is considered to be recalcitrant and indigestible by animals. A strong sulphuric acid solution (0.7 g $g^{-1}$) leaves only the most recalcitrant fibre fraction, commonly referred to as acid detergent lignin (ADL). The organic matter quality parameters governing the degradation of faeces after excretion, and in soils, are similar to those governing digestibility (Chesson, 1997) . However, in faeces the ADL fraction includes not only lignin but substantial amounts of recalcitrant microbial cell wall residues.

Plant materials may also contain soluble compounds which reduce digestibility. Condensed tannins (or proanthocyanidins), phenolic compounds, are commonly found in feed legumes and especially in browse from trees and shrubs (Le Houérou, 1980; Palm et al., 2001a). In high concentrations, they reduce degradation rate and affect feed intake and digestibility of protein and carbohydrates because they precipitate salivary or feed proteins to form complexes that are stable at rumen pH (Reed, 2001). Proanthocyanidins also reduce cell wall digestibility by binding bacterial enzymes and forming indigestible complexes with cell wall polysaccharides (Reed et al., 1990). When cattle consume legumes with large concentrations of proanthocyanidins, faecal ADL and neutral detergent insoluble N (ADIN) fractions are larger than those in the plant material consumed (Wiegand et al., 1995); proanthocyanidins cause the formation of detergent insoluble complexes that increase these fractions in the faeces. The formation of these complexes reflects the reduced digestibility of the dietary protein.

Most of the protein consumed in the diet by ruminants is hydrolysed in the rumen. Much of the ammonia liberated, together with some free amino acids is assimilated into microbial protein in the rumen (Ørskov, 1992). Ammonia that is not utilised diffuses through the rumen wall and is transported to the liver where it is converted to urea. Some of the urea is returned to the rumen in saliva, or via the bloodstream, but most is removed from the blood by the kidneys and is excreted in the urine. In the lower digestive tract, dietary protein that escaped rumen fermentation and the microbial protein synthesised in the rumen are both subject to hydrolysis, releasing small peptides and amino acids, which are absorbed into the bloodstream (Webb and Bergman, 1991). The amino acids and peptides are then utilised for the synthesis of milk protein and body tissue protein. Undigested protein passes into the large intestine, where there is a small amount of further digestion, but most is excreted in the faeces. Ruminants can decrease losses of urea through reabsorption in the kidneys when the N supply is restricted (Marini and Van Amburgh, 2001).

### *3.2.2 Partitioning of dietary N into milk, meat and excreta*

The concentration of nutrients in animal tissues and in blood, at least in forms that are metabolically active, is maintained relatively constant by homeostatic mechanisms, irrespective of the diet composition (Whitehead, 2000). Dietary N that is not used by the animal for body weight gain or milk is excreted in faeces and urine. During lactation, dietary requirements for protein are increased because about one third of the dry matter in milk is protein. The maximum utilisation of dietary N by the animal occurs when the ratio between available N and available energy is close to the optimum for the rate of live weight gain and/or amount of milk being produced. However, the lack of even one limiting amino acid can modify N utilisation by cows and reduce milk protein yield (Børsting et al., 2003). The amino acid composition of microbial protein deviates from the composition of milk, with methionine, leucine and histidine being in lower concentration than the milk's requirements. Amino acids that have been assimilated, but are in excess of what is needed to balance the most limiting amino acid, will be excreted as urea in urine.

Evidence from experiments with high-yielding dairy cattle indicates that increasing dietary N increases milk yield only when N is more limiting than energy requirements, and provided the amino acid composition of the diet meets the requirements for milk production (Børsting et al., 2003). Beyond this point, greater dietary N simply results in a greater excretion of labile N. In temperate regions, where feed is generally more N-rich than in the tropics, a greater proportion of N is usually partitioned to urine. Milk yields and dietary N are extremely different for cows in Europe and in Africa. While a Friesian cow can produce more than 30 kg of milk per day in dairy farms of Northern Europe, the same breed hardly reaches 15 kg per day in Sub-Saharan Africa (Kabuga, 1991; Ojango and Pollott, 2002).

Metabolic materials excreted in faeces include endogenous substances (salts of fatty acids, bile salts, some sloughed-off animal cells, mucus and keratinized tissue) and microbial debris (bacterial cell walls from rumen bacteria and some whole cells from fermentation in the lower tract). Microbial cell walls consist of substituted glucosamine (muramic acid) polymers with attached peptides. The large proportion of microbial cell wall in faeces indicates its resistance to degradation (Van Soest, 1994). Faecal N is largely contained in indigestible microbial matter, which is produced approximately in proportion to dry matter intake. Undigested feed, microbial and endogenous N were estimated to account for 16, 55 and 29% of faecal N respectively in dairy cows supplemented with concentrates (Larsen et al., 2001).

Faecal N varied considerably across experiments using steers (Table 2) and dairy cows (Table 3), from 19 to 136 g N animal$^{-1}$ d$^{-1}$, but the range of urinary-N was even greater (0.1 to 444 g N animal$^{-1}$ d$^{-1}$). This variation was associated with the N intake by the cattle (Fig. 4). Faecal N concentrations less than 1% are common in the tropics, while in temperate regions they are often above 3% due to the higher quality diets. Urine normally contains 4–12% of dissolved solid material, much of which consists of nitrogenous compounds. The N concentration in urine is usually between 2–20 g l$^{-1}$. Urea generally accounts for between 60 and 90% of total urinary-N, the rest consisting of other nitrogenous compounds such as hippuric acid, allantoin, uric acid, xanthine, hypoxanthine, creatine and creatinine. The C:N ratio of urine is generally within the range (2–5):1 (Whitehead, 1995). The N contents of faeces and urine may vary between individuals, on different days and on different times of the day, and reflects the variability in individual N intake. Urinary N is very susceptible to loss, and so increasing dietary N above amounts that can be readily assimilated by the animals is likely to lead to less efficient N recycling (Powell and Williams, 1993).

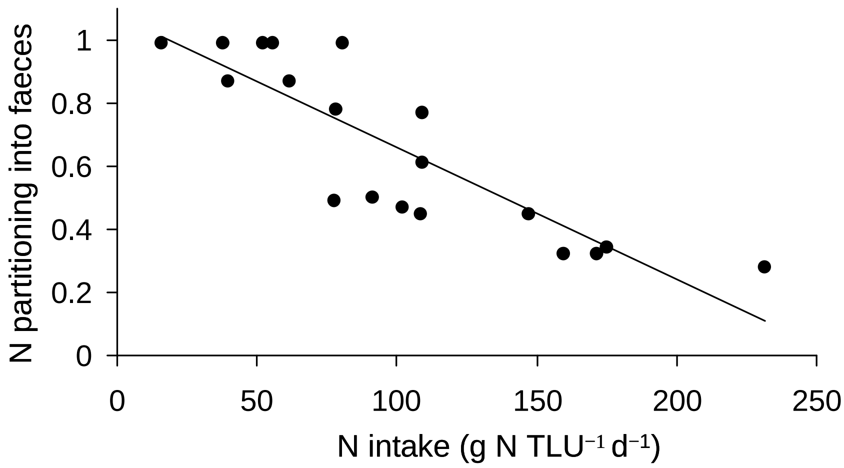


Figure 4: Effect of nitrogen intake on the proportion of intake recovered in faeces. Regression line: $y = -0.004x + 1.076$ ($P$-value < 0.01), $r^2 = 0.74$***. After Betteridge et al. (1986), Schlecht et al. (1995), Delve et al. (2001) and Lekasi et al. (2001).

Table 2: Nitrogen intake, excretion of faecal N and urinary N all expressed as per tropical livestock unit (TLU, animal of 250 kg body mass) and per day, and calculated partial and total N recovery efficiency in excreta.

| Diet | Season | Animal type | N intake (g $TLU^{-1}$ $d^{-1}$) | Faecal N (g $TLU^{-1}$ $d^{-1}$) | Urine N (g $TLU^{-1}$ $d^{-1}$) | Excreta N (g $TLU^{-1}$ $d^{-1}$) | N partitioning into faeces | N recovery efficiency | Country | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| Rangeland pasture | Dry | Male zebu | 78 | 39 | 41 | 80 | 0.49 | | Mali | Schlecht et al. (1995) |
| Rangeland pasture | Dry | | 102 | 47 | 54 | 101 | 0.47 | | | |
| Pasture + supplementation | Dry | | 91 | 47 | 47 | 94 | 0.50 | | | |
| Pasture + supplementation[1] | Dry | | 109 | 48 | 59 | 107 | 0.45 | | | |
| Rangeland pasture | Rainy | | 175 | 53 | 103 | 156 | 0.34 | | | |
| Rangeland pasture | Rainy | | 147 | 58 | 71 | 129 | 0.45 | | | |
| Napier, concentrates, poultry litter | Rainy to dry | Friesian steers | 109 | 41 | 12 | 53 | 0.77 | 0.48 | Kenya | Lekasi et al. (2001) |
| Napier, concentrates | | | 78 | 36 | 10 | 46 | 0.78 | 0.65 | | |
| Maize stover, concentrates | | | 109 | 31 | 20 | 50 | 0.61 | 0.46 | | |
| Pasture mixture[2] | Warm and rainy | Aberdeen Angus steers | 172 | 41 | 88 | 129 | 0.32 | | New Zealand | Betteridge et al. |
| Pasture mixture[3] | Cold | | 160 | 35 | 73 | 107 | 0.32 | | | (1986) |
| Pasture mixture[4] | Warm and dry | | 231 | 36 | 93 | 129 | 0.28 | | | |
| Barley straw | | | 16 | 19 | 0.1 | 19 | 0.99 | 1.21 | Kenya | Delve et al. (2001) |
| Barley straw, 15% *C. calothyrsus* | Rainy to dry | Friesian Ayrshire steers | 53 | 36 | 0.3 | 36 | 0.99 | 0.68 | | |
| Barley straw, 30% *C. calothyrsus* | | | 81 | 48 | 0.2 | 48 | 0.99 | 0.59 | | |
| Barley straw, 15% *M. axillare* | | | 38 | 27 | 0.1 | 27 | 0.99 | 0.70 | | |
| Barley straw, 30% *M. axillare* | | | 56 | 31 | 0.2 | 32 | 0.99 | 0.56 | | |
| Barley straw, 15% poultry manure | | | 40 | 28 | 4.4 | 33 | 0.87 | 0.83 | | |
| Barley straw, 30% poultry manure | | | 62 | 39 | 5.8 | 44 | 0.87 | 0.72 | | |

[1] Supplements consisted of cowpea hay and rice meal
[2] Pasture mixture: 43% ryegrass, 27% white clover, 18% other species (grass and flat weeds) and 12% dead material
[3] Pasture mixture: 68% ryegrass, 21% white clover, 6% other species and 5% dead material
[4] Pasture mixture: 72% ryegrass, 11% white clover and 17% dead material

Table 3: Milk yield, N intake and partitioning of N into milk, faeces and urine for dairy cows that received different diets. Liveweight ranged between 600-690 kg $cow^{-1}$ for Holstein cows and it was 420 kg for the crossbreed cows.

| Diet | Breed | Milk yield (kg $d^{-1}$ $cow^{-1}$) | N intake (g $d^{-1}$ $cow^{-1}$) | Milk N (g $d^{-1}$ $cow^{-1}$) | Milk N recovery | Manure N (g $d^{-1}$ $cow^{-1}$) | Faecal N (g $d^{-1}$ $cow^{-1}$) | Faecal N recovery | Urine N (g $d^{-1}$ $cow^{-1}$) | Urine N recovery | N recovery efficiency | Country | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Clover-ryegrass, low N[1] | Holstein | 26.4 | 549 | 142 | 0.26 | | 136 | 0.25 | 284 | 0.52 | 0.76 | Denmark | Petersen et al. (1998b) |
| Clover-ryegrass, high N | | 25.2 | 722 | 142 | 0.20 | | 136 | 0.19 | 444 | 0.62 | 0.80 | | |
| Roughage, concentrates, low N[2] | Holstein | 33.4 | 411 | 171 | 0.41 | 225 | | | | | 0.55 | Sweden | Frank and Swensson |
| Roughage, concentrates, high N | | 35.4 | 552 | 180 | 0.33 | 318 | | | | | 0.58 | | (2002) |
| Roughage, concentrates, low N[3] | Holstein | 33.2 | 695 | 166 | 0.24 | | | 0.46[4] | 210 | 0.30 | 0.76[4] | USA | Sannes et al. (2002) |
| Roughage, concentrates, high N | | 33.7 | 824 | 169 | 0.20 | | | 0.45[4] | 289 | 0.35 | 0.80[4] | | |
| Hay, concentrates | Friesian×Zebu | 6.5 | 190 | 32 | 0.17 | | 113 | 0.59 | | 0.24[4] | 0.83[4] | Ethiopia | Khalili and Varvikko |
| Hay, concentrates: sebania (2:1)[5] | | 5.8 | 174 | 28 | 0.16 | | 108 | 0.62 | | 0.22[4] | 0.84[4] | | (1992) |
| Hay, concentrates: sesbania (0.5:1) | | 5.2 | 162 | 22 | 0.14 | | 90 | 0.56 | | 0.30[4] | 0.86[4] | | |
| Hay, sesbania | | 4.6 | 138 | 20 | 0.14 | | 70 | 0.51 | | 0.35[4] | 0.86[4] | | |
| Hay, concentrates | Friesian×Zebu | 5.2 | 181 | 25 | 0.14 | | 108 | 0.60 | | 0.26[4] | 0.86[4] | Ethiopia | Varvikko and Khalili |
| Hay, concentrates: tagasaste (2:1)[6] | | 5.2 | 168 | 24 | 0.14 | | 95 | 0.57 | | 0.29[4] | 0.86[4] | | (1993) |
| Hay, concentrates: tagasaste (0.5:1) | | 4.4 | 149 | 19 | 0.13 | | 83 | 0.56 | | 0.31[4] | 0.87[4] | | |
| Hay, tagasaste | | 4.0 | 112 | 17 | 0.16 | | 58 | 0.52 | | 0.32[4] | 0.84[4] | | |

[1] In addition to grazing, cows received 139 g N $d^{-1}$ (low N) or 304 g N $d^{-1}$ (high N) as concentrates
[2] Roughage consisted of grass hay, grass silage and beet pulp silage and concentrates were formulated with rapeseed, brewers' grain, dried beet pulp fibre and linseed cake
[3] Roughage consisted of alfalfa hay, corn silage, and cotton seeds and concentrates were formulated with ground corn and sucrose. The high N diet had 5% soybean meal.
[4] Calculations were made under the assumption that lactating cows do not retain tissue N and there is no weight gain during lactation.
[5] Concentrates replaced by sesbania (*Sesbania sesban)* forage at ratio of 2:1 and 0.5:1.
[6] Concentrates replaced by tagasaste *(Chamaecytisus proliferus* ssp. *palmensis)* forage at ratio of 2:1 and 0.5:1.

### *3.2.3 Effect of diet on N partitioning*

Adding fermentable carbohydrate to the diet of cattle increases the microbial requirement and promotes utilisation of excess ammonia and, as a result, larger amounts of more recalcitrant faecal N may be recycled into the farming system (Delve et al., 2001). Conversely, low N intake is associated with retention of a large proportion of the dietary N for milk or weight gain, and thus low partitioning to excreta. With low N intake, a large portion of the metabolised N is recycled through the rumen, and in extreme cases there may be net loss of N (Delve et al., 2001), which will cause the death of the animal if sustained. This situation is likely to occur towards the end of the dry season, when only poor quality fodder is available. Protein-poor diets can be supplemented with a range of high N content materials such as urea, poultry manure or legumes to reduce the N limitation on rumen microorganisms. When a N-poor barley straw basal diet was supplemented with legumes or poultry manure, the recovery of N in the excreta of steers was increased (Delve et al., 2001). Poultry manure diets also resulted in a large excretion of urinary-N. However, supplementing with legumes may not provide benefits if these are low in N content or have substantial amounts of soluble polyphenols. Calliandra (*Calliandra calothyrsus* Meissn.), which has a high tannin content, and Archer (*Macrotyloma axillare* Verdc. Cv. Archer), low in tannins, did not modify N partitioning to faeces when supplemented to barley straw, which might be related to the low N content of these materials. Similarly, supplementing the diet of dairy cows with sesbania (*Sesbania sesban* Merrill.) or tagasaste (*Chamaecytisus proliferus* ssp. palmensis (L.f.) Link (Christ) Kunkel) depressed feed intake, N intake and milk production (Khalili and Varvikko, 1992; Varvikko and Khalili, 1993) (Table 3). This can be attributed to a reduction in N availability due to soluble phenolic compounds in these materials.

### *3.2.4 Partial NUE in the livestock sub-system*

There are several sources of uncertainty on the estimation of N recovery into excreta. Spanghero and Kowalski (1997) reviewed a number of N balance experiments with lactating cows and indicated underestimation of faecal N and urinary-N or unaccounted dermal losses as sources of error. Losses of ammonia after excretion of faeces and before drying of samples cause underestimation of faecal N, and volatile N losses cause underestimation of urinary-N unless urine is collected in dilute acid solution. Dermal N losses are very difficult to estimate and are usually ignored, but are probably small. N recovery into excreta varied in steers from 46% to 121% (Table 2) and in dairy cattle from 55% to 87% (Table 3), although in African dairy studies the minimum recovery into excreta was 83%. This agrees with the conclusion of Reynolds and de Leeuw (1995) that livestock in tropical smallholder systems retain less than 20% of ingested N for productive purposes.

### 3.3 Sub-system 2: Excreta collection and handling

This section includes the collection of manure as affected by cattle management and cattle housing features.

#### *3.3.1 Partitioning of excreta between stall and pasture*

The amount of manure that can be collected depends on cattle management. In zero-grazing systems, where animals are confined all day, almost all N contained in the excreta could be recycled if properly managed. Herded cattle, by contrast, excrete N where they are grazing and while this N is potentially useful for fertilising pastures, and crop fields being grazed after harvest, it is also susceptible to loss. Manure may also be collected from pastures for use on arable land or, particularly in Ethiopia, as cooking fuel. Ayantunde (1998) observed no difference in faecal excretion rate between cattle grazing during the day or during the night in Toukounous, Niger. Defecation in the stall overnight (from 18.30 to 7.30 hours) accounted for 43% of total daily faecal excretion during the dry season in Central Mali (Schlecht et al., 1995). The excretion rate was slowest during the night and fastest during the day for sheep in Niger (Fig. 5). Faecal output is proportional to feed intake, and if animals do not have access to feed during the night, nocturnal faecal excretion is reduced.

Cattle grazing in temperate rangelands defecate less than half as often as cattle in intensive conditions (Barrow, 1987), which could be explained by lower rates of feed intake. Betteridge et al. (1986) observed that urination during the night was less frequent but this was compensated by higher volume and N concentration than during the day, so N output in urine during night and day were approximately balanced. Assuming that animals graze 12 hours per day, that the urinary-N output rate is constant and that faecal N output is lower during the night, the excreta N deposited in the kraal/boma would be less than half the total N excreted during the day.

Manure that accumulates in cattle stalls may be collected at variable intervals or at the end of the dry season, to be composted or applied directly to cropland. Often the kraal is used to store manure (*in situ* storage). Following our conceptualisation of the farming system (Fig. 1 and 2), such manure management implies that the partial NCE of

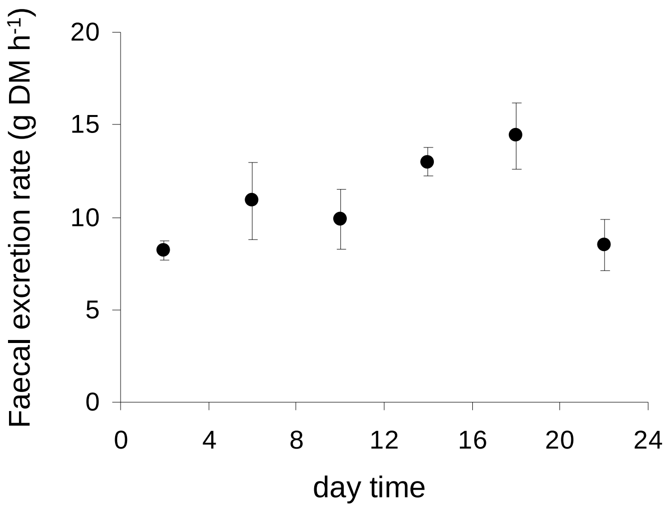


Figure 5: Diurnal variation in faecal excretion rates by sheep fed *ad libitum*. Bars represent standard errors of the mean. Source: Fernández-Rivera et al. (1995).

step 2 and 3 (collection and storage) are summarised in one NCE and that no distinction can be made to identify inefficiencies.

This sort of management represents a by-pass from sub-system 2 to 4, for which there are no quantifications of losses and factors controlling them. Manure deposited directly onto pasture or croplands is discussed in relation to sub-system 4.

*3.3.2 Factors affecting the efficiency of manure N collection from stall*

Losses of N before collection may be substantial, and depend on the management of the manure and the design of the stall. Urinary-N is particularly susceptible to loss. Leaching can be reduced by roofing the stall, and prevented by hard flooring. Volatilisation of ammonia can be minimised by using straw to absorb ammonia from freshly excreted faeces and urine. Most farmers in Central and western Kenya have some type of improved cattle-housing structure: partial roofing, solid floor, feeding trough, etc. (Shepherd et al., 1995; Lekasi et al., 2003). In contrast, the use of bedding to capture urine is very variable among farmers and is probably related to availability of crop residues and labour costs. Addition of urine did not change the nutrient concentration of the manure (Lekasi et al., 2003), which suggests that urinary N was not effectively conserved by the current management practices in the Central highlands of Kenya. Nzuma and Murwira (2000) found that addition of straw to faeces reduced ammonia losses by up to 85% and when added to combined faeces and urine, losses were reduced by 50%. The most effective mixture for composting of manure to straw to reduce N losses was 8:1.

In many regions of Africa, farmers apply large amounts of manure, e.g. 40 t $ha^{-1}$ (Probert et al., 1995), but this is of poor quality and ineffective as a source of nutrients. Poor manure quality is closely related to the management of the excreta during corralling of the animals. Probert et al. (1995) observed that cattle spend at least 16 hours per day in small stalls in semi-arid Eastern Kenya, where they were fed crop residues. At the end of the dry season, manure is collected from the stalls, usually composted for a short period and then applied to croplands. Over time, the stall becomes a shallow pit because of the digging out of manure. Total N contents of the manure ranged from 0.23 to 0.70%, but ash contents ranged from 79 to 94% because of mixing with soil from the floor of the stall. The effect was greater on sandy soils. Similar observations were made by Nhamo et al. (2004), who found that total N ranged from 0.4 to 1.2% and ash content ranged from 27 to 92% in manure from different smallholder farms in Zimbabwe. Only 7% of the manures had ash contents lower than 40%. Soil contamination of manure reduces N concentration and increases handling costs. In itself soil contamination does not reduce the total amount of N, but it is often associated with conditions that promote N loss through leaching which further reduces the fertiliser value of the manure.

Important improvements in manure quality may be achieved through flooring and roofing of the stalls, though this requires investment of capital and labour, which are generally restricted for subsistence smallholders in Africa. There appear to be opportunities to use ash content or a finger test of texture to estimate the inert fraction of the manure, but prediction of the mineralisation of the organic N fraction from manures remains problematic.

### *3.3.3 Partial NCE in the excreta collection and handling sub-system*

Manure collection is the sub-system with the highest uncertainty in determining overall NCE. The amount of N that can be collected depends largely on livestock management, which means that NCE for excreta collection and handling is site-specific. For example, if manure is collected only in stalls, it appears that less than the 50% of total N excreted during the day can be used for recycling within the farm. Increased manure collection reduces inputs into pastures, which has implications for pasture quality and degradation in the long term. However, collected manure can be used in ways that are more efficient or economically productive. In zero grazing systems, almost all excreted N could be collected but a proportion of manure N is always lost immediately through $NH_3$-N volatilisation after excretion. How much is lost depends on the use of bedding and the frequency of manure collection. When manure accumulates in the stall through the dry season and is collected just before the start of the rainy season, little of the excreted N is actually recycled.

While it is possible to collect nearly all of the excreta (up to 99% was collected in an experimental study by Lekasi et al., 2001), in practice the efficiency of collection of excreta N is usually much less. Even in the study of Lekasi et al. (2001), where manure was stored in a covered concrete storage, up to 40% of the N was lost before composting (Table 4). Manure is commonly left in kraals for weeks or months before collection, and losses of urinary-N and labile faeces N through leaching and volatilisation are likely to be very large. Assuming that 45% of excreta N is partitioned into faeces (average for steers, Table 2), that all urinary-N is lost when no bedding is used, that 43% of total excreta are left in the stall during the dry season, and that up to 70% of faecal N can be lost through volatilisation, denitrification and leaching (Martins and Dewes, 1992), we estimate the minimum for this partial NCE to be less than 10%.

Table 4: N recovery efficiencies during handling and composting of N from manure (faeces with or without addition of straw, urine or feed refusals) from Friesian steers in Central Kenya. After Lekasi et al. (2001).

| Manure type | N fresh manure[1] (kg) | N after storage[2] (kg) | Handling efficiency | Compost N[3] (kg) | Composting efficiency | Overall efficiency |
|---|---|---|---|---|---|---|
| Faeces, urine + straw (1:0.6) | 3.73 | 3.65 | 0.98 | 3.18 | 0.87 | 0.85 |
| Faeces + straw (1:1) | 2.93 | 2.50 | 0.85 | 1.85 | 0.74 | 0.63 |
| Faeces | 1.90 | 1.45 | 0.76 | 1.13 | 0.79 | 0.59 |
| Faeces, urine | 2.88 | 1.83 | 0.63 | 1.55 | 0.85 | 0.54 |
| Faeces + feed refusals | 2.48 | 2.45 | 0.99 | 1.63 | 0.67 | 0.66 |
| Faeces, urine + feed refusals (mixed manually) | 3.60 | 2.28 | 0.63 | 1.40 | 0.61 | 0.39 |
| Faeces, urine + feed refusals (mixed by cattle) | 3.73 | 2.25 | 0.60 | 1.38 | 0.61 | 0.37 |

[1] Manure N contained in a heap as produced by 61 steers per day.
[2] Manure N as produced daily by one steer and accumulated over 61 days in a roofed concrete floored barn.
[3] Manure N after composting for 90 days.

### 3.4 Sub-system 3: Manure storage (composting)

Collected manure is commonly composted in a heap or pit, alone or together with bedding, crop residues and household waste. Some collected fresh manure is also applied directly to crops, though in Western Kenya this amount was estimated to be small in proportion to the total amount of manure produced (Shepherd et al., 1995). Compost heaps are usually not protected from rain or sun, but are often mixed once or twice during the storage period of six months. Changes and losses occur during composting. The composting process and the organic materials that are added determine the quantity and quality of the final manure and, to a certain extent, the crop response to the manure N. Most farmers from Mangwende, Zimbabwe, heap the manure to compost it before application to croplands (Nhamo et al., 2004). Literature on composting manure is very scarce for Africa. Research has concentrated on crop response to composted manure and mostly the origin of that manure is not specified. What happens to the manure between excretion and application to fields has a large impact on N availability for crops.

*3.4.1 Nitrogen losses from different manure heaps*

Factors controlling the magnitude of N losses from manure heaps have been investigated in several studies (Tables 4 and 5). Losses of N occur from labile N pools, and are thus more likely when there is a high proportion of labile material. Gaseous losses of N may occur as $NH_3$ when ammonium concentrations and pH are high in the heap. The process is controlled by the availability of easily decomposable C and N, and N losses decrease abruptly as soon as the $NH_4$-N is immobilised. Murwira (1995) observed that $NH_3$-N losses did not exceed 4% of total N for a 30 day period, coincided with maximum microbial activity and appeared to reflect the size of the labile N pool.

Although ammonium-N is the predominant form of mineral N in manure heaps, nitrate-N may be formed in the surface, more aerobic layers, and is susceptible to loss by denitrification. Denitrifying bacteria require anaerobic conditions, and denitrification of labile N is only likely if oxygen becomes depleted in zones of heaps where nitrate-N is present, or in microsites within it. Denitrifiers also require sufficient moisture; at low water content, oxygen availability appears to have a negligible effect on N losses during composting (Kirchmann and Witter, 1992).

Soluble N may be leached if there is throughput of water. Heaping manure reduces its surface area, and so decreases leaching compared with uncollected manure. Leaching occurs during the first days of composting and is increased when heaps are turned (Martins and Dewes, 1992). Most N in the leachate was $NH_4$-N, the second fraction was organically bound N while $NO_3$-N represented only a small proportion of the total N (0.1–2.2%) in the experiments of Martins and Dewes (1992).

Table 5: Nitrogen losses from different types of manures during laboratory incubations, aerobic or anaerobic composting.

| Manure type | Treatment | Period (days) | Initial N (%) | Moisture content (%) | $NH_4$-N losses (% initial N) | $NO_x$-N losses (% initial N) | N leaching (% initial N) | Factors driving losses | Country | References |
|---|---|---|---|---|---|---|---|---|---|---|
| Fresh faeces | Anaerobic incubation | 15 | 1.26 | 579* | 1.1 | | | Size of mineral N pool | Zimbabwe | 1 |
| | | | 1.24 | 781* | 0.7 | | | Size of mineral N pool | | |
| | | | 1.11 | 986* | 1.0 | | | Size of mineral N pool | | |
| Stall manure mixed with refusals | Aerobic incubation | 30 | 1.90 | 12* | 1.2 | | | Moisture, microbial activity | | |
| | | | | 36* | 0.5 | | | Moisture, microbial activity | | |
| | | | | 48* | 0.6 | | | Moisture, microbial activity | | |
| | | | | 60* | 1.5 | | | Moisture, microbial activity | | |
| | | | | 72* | 3.6 | | | Moisture, microbial activity | | |
| | | | | 84* | 2.2 | | | Moisture, microbial activity | | |
| | | | | 100* | 2.0 | | | Moisture, microbial activity | | |
| Fresh faeces dried before composting | Aerobic composting | 210 | 2.3 | 50 | 0.1 | | | Moisture, size of mineral N pool? | Sweden | 2 |
| Fresh faeces dried before composting | Anaerobic composting | | 2.3 | 50 | 0 | | | Moisture, anaerobic conditions | | |
| Fresh liquid manure | Aerobic incubation | 16 | 0.54 | 88 | 6.0 | | | Temperature | Germany | 3 |
| Fresh liquid manure + straw (1: 0.05) | Aerobic incubation | | 0.54 | 84 | 10.8 | | | Temperature, microbial N immobilisation | | |
| Fresh liquid manure + straw (1: 0.30) | Aerobic incubation | | 0.52 | 69 | 5.9 | | | Temperature, microbial N immobilisation | | |
| Sheep faeces + urine + straw (9:10:3) | Aerobic composting | 86 | 3.1 | 71 | 46 | | | Temperature, aerobic conditions | Denmark | 4 |
| Sheep faeces + urine + straw (9:10:3) | Anaerobic composting | | 3.1 | 71 | 18 | | | Anaerobic conditions | | |
| Fresh liquid manure | Aerobic composting | 51 | 0.60 | ? | 23.7 | | | Size of mineral N pool (% of urine N) | Switzerland | 5 |
| Cattle urine-rich liquid manure | | | 0.73 | | 49 | | | Size of mineral N pool (% of urine N) | | |
| Cattle faeces + straw (1: 0.025) | | | 0.50 | | 11.4 | | | C availability, microbial N immobilisation | | |
| Cattle manure + straw (1: 0.18) | | | 0.51 | | 10.6 | | | C availability, microbial N immobilisation | | |
| Fresh liquid manure + straw (1: 0.55) | Aerobic composting | 114 | 0.55 | 85 | 49 | <5 | 17 | Temperature, irrigation, turning of the heaps | Germany | 6 |
| Fresh manure mixed with straw | Aerobic composting | 64 | 0.67 | 82 | 5 | 13 | 4 | Size of mineral N pool | Denmark | 7 |

* % of water holding capacity

References: 1. Murwira, 1995, 2. Kirchmann and Witter (1992), 3.Dewes (1999), 4. Thomsen (2000), 5. Külling et al. (2001), 6. Martins and Dewes (1992), 7. Petersen et al. (1998a)

Anaerobic conditions are more likely to develop when the heap has a high bulk density or if it is tightly covered. However, these conditions also slow the diffusion of gaseous N out of the heap, and if N demand from microorganisms later increases then $NH_3$-N may be reincorporated into organic matter. In a study by Thomsen (2000), manure composted aerobically lost 46% of its total N after 86 days of storage, whereas anaerobically composted manure lost only 18%. Most of the N lost was from urine, though as composting progressed the relative contribution of faeces-N and straw-N to N losses increased. In the anaerobically composted manure, 48% of its total N was present as mineral N, mostly $NH_4$-N, at the end of storage.

The relative importance of different pathways of N loss has been studied in few trials, but these report that the greatest N losses during aerobic composting are through gaseous emissions (Table 5). Martins and Dewes (1992) found that turning manure heaps stimulated a loss of 49% of N as $NH_3$, probably by stimulating aerobic microbial activity and allowing better aeration. In a study where the heap was not turned but the surface was in contact with the atmosphere, denitrification losses were more important (Petersen et al., 1998a). Volatilisation of $NH_3$ seems likely to cause the largest N losses during composting; only 4–17% of N was lost through leaching or denitrification in these studies. Most of the above studies relate to situations where manure heaps were covered. When manure heaps are uncovered, as is often the case in Africa, leaching losses will be of greater importance.

### *3.4.2 Partial NUE in the manure storage sub-system*

The N in manure after composting ranged from around 37% to 85% of the N initially present. Opportunities exist to increase N recovery from the storage process. For example, addition of straw to manure increases the labile C pool, promoting immobilisation of labile N, although adding straw commonly produces a temperature rise early in the composting process that can increase ammonia losses (Dewes, 1999). Anaerobic composting can reduce N losses and result in a final manure richer in available N, which makes it more immediately effective, although it also increases the risk of loss of manure N after application to the soil.

## **3.5 Sub-system 4: Soil availability, crop capture and crop conversion**

The partial efficiencies for these three stages in the transformation of manure N added to soils into useful plant-protein have been relatively well-studied (Fig. 3), but different studies have used different boundaries between the stages. Quality and rates of application of organic materials vary widely. Small-scale farmers from communal areas in the Masvingo province of Zimbabwe apply on average 5 t $ha^{-1}$ of manure, mixed with small amounts of leaf litter (Mugwira and Murwira, 1997). In the Kano zone of Nigeria, one of the most intensive farming systems of West Africa (Harris and Yusuf, 2001), with few remaining cattle and no rangelands, manure is a poor quality, heterogeneous mixture of organic materials and ash, and farmers apply 18 t $ha^{-1}$ to achieve crop yield responses. Probert et al. (1995) reported applications of up to 40 t $ha^{-1}$ in semi-arid Kenya. Crop responses depend on the rate of application of N, as determined by manure quality and application rate, but also on other manure quality factors, crop characteristics and environmental conditions.

### *3.5.1 Mineralisation of N from organic materials*

Accurate predictions of N mineralisation from organic materials in soil remain elusive, since interactions between the differentially labile carbon (C) and N pools are complex and strongly influenced by environmental conditions. However, an understanding of the main factors has developed, notably for plant materials applied directly to soil (Palm et al., 2001a). The release of N is governed by the N demand of micro-organisms, which is a function of the availability of C sources for microbial growth. The presence of labile C increases the demand for labile N and therefore suppresses N release. Plant materials also often contain lignin which is recalcitrant for decomposition and soluble polyphenols, which bind to proteins and thus retard N mineralisation.

Mineralisation of N is essential to release N for plant uptake, but if N concentrations rise because of a large release of N from labile pools when there is little plant demand for N, large losses can occur. Ammonia losses are greatly reduced if manure is incorporated to the soil. Recalcitrant C and N pools also create and satisfy microbial demand for N, respectively, but at a slower rate, and so these pools change size more slowly and have less influence over soluble N concentrations. They may however be important for soil structure and for longer-term nutrient cycling.

The release of N from manures is also governed by microbial demand, but the starting composition of manures differs from that of plant materials in several important ways. Soluble polyphenols are unlikely to be present in manures, and the stable fraction includes large amounts of glucosamine (muramic acid) polymers derived from microbial cell walls (Chesson, 1997). This may explain the limited success that has been achieved from applying plant quality indices to the prediction of manure mineralisation (Table 6). The mineralisation rate of manure N tends to be higher for manure with narrow C:N ratios, but the influence of other chemical quality factors remains uncertain. Quality parameters could not explain N mineralisation/ immobilisation in incubations in soil of fresh manure (Delve et al., 2001). All manure types released N in the first week of the incubation, but then immobilised N for 17 to 28 weeks, resulting in a lack of response in maize (*Zea mays* (L.)) growth to any of the manures in both pot and field experiments. Kyvsgaard et al. (2000) found that N mineralisation from manure was significantly negatively correlated with NDF, ADF, crude fibre and apparent digestibility of the feed. Apparent digestibility was correlated to N faecal concentration and it was proposed that faecal N could be predicted from dietary N and digestibility of the feed, which ignored N recycling in the animal and excess N excreted as urine. Because N mineralisation was correlated with faecal N, the authors concluded that N mineralisation can be predicted from feed quality.

Table 6: Initial quality parameters of manures and their effects on N mineralisation or N uptake. TSC: total soluble C, TSN: total soluble N, NDF: neutral detergent fibre, NDF-N: nitrogen in neutral detergent fibre, ADF: acid detergent fibre, ADF-N: nitrogen in acid detergent fibre, ADL: acid detergent lignin, CF: crude fibre, TEP: total extractable polyphenols. Empty cell indicates no measurements, + indicates positive effect, - negative effect and ns not significant.

| Substrate | TSC | TSN | Total C | Total N | C:N | NDF | NDF-N | NDF:N | ADF | ADF-N | ADL | CF | ash | TEP | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cattle manure | | | | ns | ns | | | | | | | | | | 1 |
| Cattle manure | | | | | - | | | | | | | | | | 2 |
| Cattle manure | ns | ns | | ns | ns | ns | ns | | ns | ns | ns | | | | 3 |
| Cattle manure | ns | ns | ns | ns | - | ns | + | | ns | | + | | ns | ns | 4 |
| Cattle manure | | + | ns | ns | + | ns | | + | + | | ns | | | | 5 |
| Cattle manure | | | + | + | - | | | | | | - | | - | | 6 |
| Sheep faeces | | | | + | | | | | | | | | | | 7 |
| Sheep faeces | | | | + | | | | | | | | | | | 8 |
| Sheep faeces | | ns | | ns | | ns | | ns | | | ns | | | ns | 9 |
| Sheep faeces | | | | + | - | | | | - | | | - | | | 10 |
| Goat manure | ns | ns | ns | ns | ns | | | | | | ns | | | ns | 11 |

References: 1. Castellanos and Pratt (1981), 2. Janssen (1996), 3. Delve (1998), 4. Lekasi (2000), 5. Van Kessel and Reeves (2002), 6. Nhamo et al. (2004), 7. Barrow (1961), 8. Floate (1970), 9. Powell et al. (1999), 10. Kyvsgaard et al. (2000), 11. Mafongoya et al. (2000).

The studies previously discussed showing partitioning of excess N into urine, and the difficulty of efficiently recycling this urinary-N within farms, suggest that factors other than feed quality need to be considered. This will be particularly true when manure handling and storage conditions are not optimal. Nyamangara et al. (1999) observed that aerobically decomposed manure with a C:N ratio of 9:1 immobilised added fertiliser N, whereas manures with a C:N ratio of 18:1 did not. They concluded that

C:N ratio of the manures is not a suitable parameter to predict N mineralisation of manures with narrow C:N.

### *3.5.2 Direct application of excreta to pastures and cropland*

A proportion of the nutrients in excreta deposited on pastures contributes to subsequent pasture production. Pasture biomass increases due to excreta are estimated to be between 27 to 38% (Weeda, 1967; During and Weeda, 1973), and are mainly attributed to the N in excreta, although growth responses to P, K, Mg and Ca may be expected in poor soils. Plants may also show responses to the animal excreta in the second year. The amount of N recycled is influenced by the amount of N in excreta, the frequency of excretion, size of each excretion and the land surface covered by excreta (Haynes and Williams, 1993). Under free-grazing conditions, cattle tend to deposit excreta in non-productive areas, such as beneath trees, around sources of water and gateways and along travelling routes. In hilly pasture excreta tends to accumulate in flatter areas. Increasing the stocking rate reduces this “camping” effect and manure is more evenly distributed over the terrain (Haynes and Williams, 1993), particularly under intensive rotational grazing management.

Plants that are actually covered by dung pats can die because of lack of light, but the growth of adjacent pasture is stimulated. Under liquid dung patches which disintegrate quickly, pasture regrowth can be rapid (Weeda, 1967). In a rotationally grazed pasture with a stocking rate of 2.5 cows $ha^{-1}$, 10% of the area was covered with faeces and urine in one year (White et al., 2001). Dung and urine patches affect an area much larger than that actually covered. Powell et al. (1998) found that sheep urine deposited in concentrated patches of 95 $cm^2$, but through lateral movement affected a total area nearly twenty times larger.

Local rates of N application within dung or particularly urine patches are extremely high, which increases the risk that this N will be lost. Urea hydrolyses rapidly after excretion, suggesting that urease activity is already present in voided urine (Haynes and Williams, 1993), causing a rapid rise in pH that promotes ammonia volatilisation. Such N losses range from 4 to 46% of urinary-N. Application of cattle urine to pasture residues during the dry season in Australia resulted in apparent loss of 46% of urinary-N from the soil-plant system (Vallis et al., 1985), and the following annual pasture took up only 6% of the N applied in the urine. In sandy soils poor in organic matter in Niger, Powell et al. (1998) observed that additions of sheep urine (localised application of 202 kg N $ha^{-1}$) increased pH, available P and $NH_4$-N in the upper 15 cm of the soil. They estimated that 30−50% of the urinary-N was lost during the first week of application. In high-N pastures, N urine losses are usually higher because the proportion of the N intake that is returned as urinary-N is higher than in poor-N pastures. Losses of $_{15}$N after urination due to leaching were estimated to be 37% under humid temperate conditions (Whitehead and Bristow, 1990). In New Zealand, it was observed that application of sheep urine increased the soil $NH_4$-N content in both short-term (2–3 years) and long-term pastures (more than 20 years) and nitrate content in the long-term pasture. This effect lasted longer in the long-term pasture because grasses consumed most of the available N in the short-term pasture. Nitrogen uptake efficiency from the urine was higher in the short-term pasture (41%) with a lower soil N content than in the long-term pasture (21%) (Williams and Haynes, 2000).

Tethering livestock in croplands may appear an attractive means of recycling N. However there are few sinks for labile N in arable soils that are not being cropped, and ammonia volatilisation and N leaching can cause loss of up to 50% of urinary-N within one week of the application. Some faecal N is also lost if manure is not incorporated into the soil. Brouwer and Powell (1995) estimated the N losses from manure produced by tethered cattle to be 91 kg N $ha^{-1}$ (34 % of the N input). In semi-arid West Africa, the amount of manure obtained by tethering livestock in cropland was influenced by rangeland productivity, consumption rate and the distance from the rangelands to the crop fields being manured (Fernández-Rivera et al., 1995).

### *3.5.3 Efficiency of N uptake*

Nitrogen uptake is limited by N availability, but also by plant N demand. Uptake efficiency thus depends on other factors affecting plant growth (varietal characteristics, and the availability of light, water and other nutrients) in relation to N availability (Janssen, 1998). Limitations by other factors explain the range of N uptake efficiency observed in the reviewed studies. In Niger, greater doses of manure N did not increase crop biomass N, but increased N losses through leaching (Brouwer and Powell, 1998). Lekasi (2000) compared poor soils in Gatuanyaga, Central Kenya, with soils in nearby Kariti which are particularly low in N but not in other nutrients, and found that P uptake from manure in Kariti was twice that in Gatuangaya, but N uptake was ten times higher. N uptake efficiencies are usually lower at sites with less rainfall (Table 7).

Many studies have looked at crop responses to manure application, but studies that address the synchronisation of N release from manure with crop uptake, attempting to minimise the risk of N loss, are rare. The difficulty of predicting the pattern of

Table 7: N uptake measured for maize crops that received application of manure N in Africa.

| Treatment | Rainfall (mm) | Cropping Season | Soil type | Incorpo-rated into soil | Manure N (kg ha $^{-1}$) | Biomass N[1] (kg ha $^{-1}$) | N uptake efficiency[2] | Overall N uptake efficiency[3] | Grain N (kg ha $^{-1}$) | N conversion efficiency[4] | Country | Ref.[7] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Control | 900 | First | coarse | Yes | 0 | 25.5 | | | | | Zimbabwe | 1 |
| Composted manure, split dose | | | loamy | | 116 | 48.7 | 0.20 | | | | | |
| Composted manure, one dose | | | sand | | 349 | 70.8 | 0.13 | | | | | |
| Control | ? | Second | | | 0 | 22.5 | | | | | | |
| Composted manure, split dose | | | | | 116 | 78.1 | 0.27 | | | | | |
| Composted manure, one dose | | | | | 0 | 96.6 | 0.24 | | | | | |
| Control | ? | Third | | | 0 | 4.5 | | | | | | |
| Composted manure, split dose | | | | | 116 | 15.7 | 0.04 | 0.26 | | | | |
| Composted manure, one dose | | | | | 0 | 18.5 | 0.06 | 0.38 | | | | |
| Control *L. leucocephala* hedgerow | 825 | First | ? | Yes | 0 | 24.5 | | | 18.6 | 0.76 | Ethiopia | 2 |
| Composted manure | | | | | 87 | 32.2 | 0.09 | | 24.6 | 0.76 | | |
| Control *L. pallida* hedgerow | | | | | 0 | 21.5 | | | 15.5 | 0.72 | | |
| Composted manure | | | | | 87 | 24.8 | 0.04 | | 17.6 | 0.71 | | |
| Control | 1300 −1600 | First | clay | Yes | 0 | 27.1 | | | 15.3 | 0.56 | Kariti, Kenya | 3,4 |
| Composted faeces | | | | | 75 | 53.5 | 0.35 | | 39.1 | 0.73 | | |
| Composted faeces + feed refusals | | | | | 75 | 59.1 | 0.43 | | 41.4 | 0.70 | | |
| Composted faeces + urine | | | | | 75 | 39.8 | 0.17 | | 27.4 | 0.69 | | |
| Composted faeces + urine + feed refusals[5] | | | | | 75 | 60.1 | 0.44 | | 44.1 | 0.73 | | |
| Composted faeces + urine + feed refusals[6] | | | | | 75 | 63.9 | 0.49 | | 41.1 | 0.64 | | |
| Control | 750 −900 | First | sandy | Yes | 0 | 15 | | | 7.5 | 0.50 | Gatuanyaga, Kenya | 3,4 |
| Composted faeces | | | clay | | 75 | 17.1 | 0.03 | | 8.2 | 0.48 | | |
| Composted faeces + feed refusals | | | loam | | 75 | 21.5 | 0.09 | | 12.3 | 0.57 | | |
| Composted faeces + urine | | | | | 75 | 12.1 | − | | 6.8 | 0.56 | | |
| Composted faeces + urine + feed refusals[5] | | | | | 75 | 20 | 0.07 | | 10.1 | 0.51 | | |
| Composted faeces + urine + feed refusals[6] | | | | | 75 | 17.5 | 0.03 | | 7.7 | 0.44 | | |
| Composted farmers' manure | 750 | First | coarse | | 133 | 15 | 0.11 | | 5.3 | 0.35 | Zimbabwe | 5 |
| Composted farmers' manure | | Second | grained sand | | 0 | 9.6 | 0.08 | 0.19 | 3.2 | 0.33 | | |

[1] Biomass N is total maize above-ground biomass N

[2] N uptake efficiency = (biomass N / (Manure N – biomass N previous season)), biomass N = (biomass N treatment – biomass N control),

[3] Overall efficiency = (total biomass N (all seasons) / total manure N)

[4] N conversion efficiency = grain N treatment / biomass N treatment

[5] Faeces, urine and feed refusals have been mixed manually before composting

[6] Faeces, urine and feed refusals have been mixed by cattle before collection and composting

[7] References: 1. Nyamangara et al. (2003a), 2. Lupwayi et al. (1999), 3. Lekasi (2000), 4. Lekasi et al. (2001), 5. Chikowo et al. (2004)

mineralisation has already been discussed. Crop N demand correlates with the rate of biomass accumulation, and is thus predictable insofar as crop development can be predicted.

More frequent application may in any case increase the synchrony and the efficiency of use of materials. Annual applications of manure to a maize-legume rotation in Zimbabwe resulted in greater N uptake efficiency in the first and second season after application than the recommended practice of applying 35–40 t manure $ha^{-1}$ once every four years (Nyamangara et al., 2003a) (Table 7).

Crop response to manure N in the first season depends on the amount of mineral N and labile N in the manure (Giller et al., 1997). Nitrogen uptake from manures in the second and subsequent seasons also depends on manure quality. In old manures much of the N is in stable forms that are only mineralised slowly, and N uptake efficiency can be greater after the first season. However, the more stable N pools may not be mineralised within a useful timescale, and it is more common to see greater uptake efficiency during the first season. Powell et al. (1999) compared the N uptake efficiency from legume leaves with that from faeces from sheep fed the legume leaves as a supplement. All faeces except those which resulted from supplementing with *Vigna unguiculata* (L.) Walp. resulted in higher N uptake efficiencies (5–14%) than the corresponding leaves (1–9%). However, there were no clear relationships between measured faecal chemical components and N uptake.

### *3.5.4 Crop N conversion*

The yield that can be produced from a certain amount of N uptake depends on the minimum concentration to which N can be diluted in the plant. Cereals can produce grain with relatively low grain N concentration, but their large grain yields require substantial quantities of N (Muchow, 1998). The N required for grain filling or the development of other useful crop parts is partly derived from current uptake, but also comes from remobilisation of N from leaves and stems. Remobilisation efficiency is affected by conditions towards the end of the crop's development. Efficiency of conversion at low N uptake is low and increases when better growing conditions increase N uptake (De Wit, 1992). Under low fertility conditions or if there is a late drought, grain development is arrested ("haying off"), and partitioning of N into grain is minimal. However, when grain is formed but N uptake is greater than that required for yield as limited by another factor, partitioning to grain tends to be higher. High grain N concentrations are thus found in crops that suffered water stress or deficiency of other nutrients.

Table 8: N uptake and N leaching measured for millet crops that received application of manure N in Africa.

| Treatment | Rainfall (mm) | Cropping Season | Soil type | Incorporated into soil | Manure N ($kg\ ha^{-1}$) | Biomass N ($kg\ ha^{-1}$) | N uptake efficiency [1] | Grain N ($kg\ ha^{-1}$) | N conversion efficiency [2] | Country | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cattle corralling | 562 | First | deep sandy | No | 0 | 13 | | | | ISC, Niger | 1 |
| | | | | | 81 | 51 | 0.47 | | | | |
| | | | | | 271 | 52 | 0.14 | | | | |
| Cattle corralling | 562 | First | Sandy, concave slope | No | 0 | 16 | | 5.3 | | ISC, Niger | 2 |
| | | | | | 59 | 25 | 0.16 | 7.8 | 0.31 | | |
| | | | straight slope | | 0 | 24 | | 7.9 | | | |
| | | | | | 81 | 82 | 0.71 | 28 | 0.35 | | |
| | | | crest | | 0 | 27 | | 8 | | | |
| | | | | | 169 | 68 | 0.25 | 21 | 0.31 | | |
| | | | convex slope | | 0 | 27 | | 8 | | | |
| | | | | | 189 | 53 | 0.14 | 16 | 0.30 | | |
| Manure farmers' fields | 350 | | | No | 19 | 4 | 0.21 | 0.5 | 0.13 | Ouallam, Niger | 3 |
| Manure farmers' fields | 425 | | | | 25 | 4 | 0.18 | 1.3 | 0.29 | Kolo, Niger | |
| Manure Experimental | 560 | | | | 44 | 9 | 0.21 | 4 | 0.41 | Sadoré, Niger | |
| Cattle corralling | | | | | 60 | 34 | 0.57 | 10 | 0.30 | | |
| Manure farmers' fields | 650 | | | | 55 | 9 | 0.16 | 2.4 | 0.27 | Say, Niger | |
| | 560 | | | | 145 | 13 | 0.09 | 4 | 0.34 | Sadoré, Niger | |
| Cattle corralling | | | | | 200 | 42 | 0.21 | 6 | 0.15 | | |
| Manure farmers' fields | | | | | 73 | 15 | 0.20 | 4 | 0.26 | Sadoré, Niger | 4 |
| | | | | | 290 | 39 | 0.13 | 14 | 0.35 | | |
| Control | 450 | First | Sandy | No | 0 | 24 | | 15 | 0.60 | Boundou, Niger | 5 |
| Cattle corralling, grazing cattle | | | | | 45 | 37 | 0.29 | 22 | 0.58 | | |
| Cattle corralling, grazing + supplement[3] | | | | | 54 | 35 | 0.24 | 21 | 0.60 | | |
| Cattle corralling, grazing + supplement[4] | | | | | 56 | 39 | 0.26 | 22 | 0.56 | | |

[1] N uptake efficiency = Biomass N / Manure N
[2] N conversion efficiency = Grain N treatment / Biomass N treatment
[3] Supplement consisted of millet bran, salt and P
[4] Supplement consisted of millet bran, salt, P, and blood meal
References: 1. Brower and Powell (1995), 2. Brower and Powell (1998), 3. Williams et al. (1995), 4. Bationo et al (1995), 5. Sangaré et al. (2002).

### *3.5.5 Partial NCE in the soil-crop sub-system*

Nitrogen uptake efficiencies from manure in Sub-Saharan Africa are generally poor, and vary considerably even at same rate of manure N application. Uptake of N in maize ranged from 3 to 49% of that applied, with one case of negative recovery, and apparent N uptake efficiency in millet (*Pennisetum glaucum* (L.) R. Br) varied from 9 to 71%. The conversion efficiency of total plant N into grain N varied from 33 to 76% for maize (Table 7) and 13 to 60% for millet (Table 8). Differences due to crop specific characteristics (crop internal efficiency) were obscured by variability corresponding to other growth factors, especially availability of water.

## 4. Overall efficiency and critical steps of N transfer

The ranges in partial NCE for each of the transfer stages from plant material through to useful plant products are summarised in Table 9. Overall NCE, calculated as the product of partial NCE at each transfer step, was less than 1% for the worst-case combination of animal production, manure handling and crop response. For the best-case combination overall NCE was 44%, but this is unlikely to reflect NCE in real farming systems since it includes both maximum recovery of feed N (121%, with extremely poor feed quality) and very well-controlled manure handling. By comparison, NCE of legume crop residues and green manures directly incorporated into the soil in the tropics varies from approximately 6 to 28% in the first season, and an extra 2 to 15% might be recovered by second or later crops (Giller and Cadisch, 1995). This suggests that livestock and manure composting can be relatively inefficient uses of N, and it is undoubtedly true that livestock increase the risk of N loss. However, as well as providing many important benefits in their own right, livestock can facilitate nutrient management by mediating spatial flows of N and by improving the availability of the N contained in organic nutrient resources. The net effect of livestock on the whole-farm nutrient balance is positive if they are stalled overnight but obtain little feed, or only low quality feed, on-farm. However, if livestock are fed on good quality feed when they are stalled overnight but graze off-farm on poor quality pastures during the day, and assuming that only 50 % of excreta are produced during the night (see Section 3.3.) they are likely to be net exporters of nutrients from the farm. A complete analysis of the potential for nutrient cycling through livestock in farming systems needs also to quantify fodder availability and feed intake, and the removal of nutrients as a result of the sale of crop and animal products. In intensive dairy systems nutrient inputs in purchased feed are often substantial, and maintain positive farm N balances.

Table 9**:** Ranges of partial nitrogen cycling efficiencies at different stages in the transfer of plant material N within crop-livestock systems. Minimum, mean and maximum values from the reviewed studies are presented. N output for livestock sub-system refers to N in excreta rather than in milk and meat.

| System | Type | Partial NCE (kg N output kg N input$^{-1}$) | | |
|---|---|---|---|---|
| | | Min. | Mean | Max. |
| 1. Livestock | African steers | 0.46 | 0.69 | 1.21 |
| | African dairy cattle | 0.83 | 0.85 | 0.87 |
| | Other dairy cattle | 0.55 | 0.71 | 0.80 |
| 2. Excreta collection and handling | All | 0.60 | 0.83 | 0.99 |
| 3. Manure storage | All | ca. 0.3 | 0.73 | 0.87 |
| 4. Soil availability, crop capture and crop conversion | Maize uptake from manures[1] | 0.03 | 0.17 | 0.49 |
| | Millet uptake from manures[1] | 0.09 | 0.31 | 0.71 |
| | Maize conversion to grain N | 0.44 | 0.63 | 0.76 |
| | Millet conversion to grain N | 0.13 | 0.35 | 0.60 |

[1] Uptake in the first season after application

## 5. Conclusions

Our review of the literature illustrates the great uncertainty that remains over several critical stages of nutrient transfer through crop-livestock systems. Studies of N partitioning in livestock and of soil N availability and crop N uptake have been relatively common, and some have included measurements of mass balances that can be used to calculate and compare efficiency. Studies of manure handling and storage are much rarer. When such studies have been carried out they have mainly recorded only manure quality, and amounts of manure or manure N produced have not been estimated. This is unfortunate since the critical step for increasing N cycling efficiency appears to be manure handling, although the range of efficiencies is large for many of the steps. There is potential for increasing the partitioning of excreted N into faeces N through a better control of the feed quality. This must be done without affecting the partitioning of N to milk and meat, which are the most valuable products. Improving the synchrony of mineralisation and crop uptake is an important theoretical principle, but because of variation in rainfall, crop demand and the slow mineralisation of N from manure, this interaction can be complex and difficult to manage with accuracy.

Techniques that reduce losses after manure excretion are relatively easy to design and implement. Improving the roofs and floors of cattle stalls can assist in minimising N losses and soil contamination of manure, resulting in a more concentrated product containing a greater amount of the N excreted. Manure storage technologies are also simple, and offer the chance to manipulate manure quality and use efficiency. Changing from aerobic to anaerobic composting reduces N losses, and results in manure which has higher concentrations of available N. The N in richer manures is more easily lost, but they are less bulky and so easier to handle, and have a more immediate effect. Improving cattle stalls and manure collection methods requires investment by farmers, and will require full analysis of the costs and potential benefits, compared with alternatives. An assessment is also needed of how well new approaches fit within the livestock management system and the whole farm livelihood. This review represents a first step in such an analysis which we are conducting under the Nutrient Use in ANimal and Cropping systems – Efficiencies and Scales (NUANCES) framework (Giller et al., 2006). Studies of individual technologies and nutrient transfer stages are invaluable in providing information for such an assessment, but cannot substitute for it. Partial nutrient use efficiencies are particularly useful for measuring sub-system performance, and studies should quantify nutrient inputs and outputs using mass balances in future. This approach makes it possible to assess the importance of each subsystem relative to overall nutrient flows, and helps to identify critical inefficiencies and intervention points for more efficient nutrient management.

# Chapter 3

## Manure as a key resource within smallholders farming systems: Analysing farm-scale nutrient cycling efficiencies with the NUANCES framework [†]

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## Abstract

Smallholder farmers in Africa recognise the important role of manure in maintaining soil fertility. For smallholder farmers who use little fertiliser, efficient management of nutrients in manure is key for crop production. We describe a simple model to analyse the effect of manure management on the efficiency of mass and nutrient retention. We used on-farm data on manure excreted and manure management, experimental results, literature and fuzzy logic to analyse losses during manure storage. The model was used the model to analyse N cycling efficiency (NCE) within smallholder farms in western Kenya. Simulations showed that manure management during collection and storage had a large effect on the efficiency of mass and nutrient retention. Differences in NCE between farms of different wealth classes arose due to differences in resource endowment. For poorer farmers, large N losses occur at all stages of manure cycling. Urinary-N losses occurred on all farms but their impact on NCE for poor and medium-class farmers was larger due to the smaller amount of N recycled. With current management the poor farmer recovered <1 kg N $y^{-1}$ in composted manure from 15 kg N $y^{-1}$ excreted. Improved manure storage had little effect on increasing overall NCE for the poor farmer due to large losses before storage. For the wealthier farmer improvement of manure storage increased NCE and allowed the recycling of 30% of N excreted (ca. 30 kg N $y^{-1}$) with small investment in infrastructure. Covering manure heaps with a polythene film reduced mass and N losses considerably. For the poor to increase overall NCE, investment in cattle housing and recycling of urinary-N is required. Increasing cattle numbers or improved feeding would have a larger effect on manure availability but this is constrained by feed scarcity and investment capacity. The absolute amounts of N recycled (1−6, 4−17 and 7−18 kg N $y^{-1}$ for poor, medium and wealthier farmers) were small compared with maize crop N demand (>50 kg N $ha^{-1}$), but significant given the small farm sizes (0.1–1.1 ha). Although absolute amounts of N recycled with improved manure management may have little immediate impact on crop productivity, manure is often the only input available. Manure provides other nutrients for crops and maintains soil organic matter – both vital to guarantee efficient use of fertiliser N – which justifies the search for interventions to assist farmers to make better use of manure.


**Keywords:** Sub-Saharan Africa, NCE, fuzzy logic modelling, FARMSIM, HEAPSIM

# 1. Introduction

Although manure is seen as a problematic waste in intensive agricultural systems in developed countries, it is a key resource to sustain crop productivity of the majority of smallholder farming systems in Africa (Giller et al., 2002). Steinfeld et al. (2006) recently indicated that the contribution of livestock to climate change through gas emissions is more important than that of the transport sector, and that climate change mitigation measurements must include reducing the amount of meat in humans' diets. But in Africa, farmers keep livestock for other purposes than only meeting their meat consumption, for instance as a source of capital, for social status and for manure production. Farmers recognise the important role of manure in maintaining soil fertility – largely because much of their land is poorly productive due to continuous cultivation on soils that are often inherently poor in nutrients and receive little fertilisers. Manure is often a scarce resource, and livestock are the central means of concentrating nutrients within farming systems, resulting in inequitable redistribution of nutrients from common to cultivated lands and often also from farms of poorer to richer households. Crop productivity gains are achieved by concentrating organic matter and nutrients in homefields, at the long-term expense of declining productivity in remote fields and common lands (Tittonell et al., 2007; Zingore et al., 2007b). As most smallholder farmers use little mineral fertiliser, due to the high cost and/or poor distribution of rural markets, the efficient management of nutrients through manure recycling within the crop-livestock system is key to support food production.

Rufino et al. (2006) – Chapter 2, conceptualised African farming systems in four sub-systems through which nutrient transfer takes place: 1. Livestock: animals partition dietary intake into growth and milk production, faeces and urine; 2. Manure collection and handling: housing and management determine what proportion of the animal excreta (and the nutrients contained in it) may be collected; 3. Manure storage: manure can be composted (or simply stored) with or without addition of plant materials, during varying periods of time, and under different storage systems (e.g. pits, heaps, roofed stalls, etc.); 4. Soil and crop conversion: a proportion of the nutrients in organic materials applied to soil becomes available, part of which is taken up by plants, of which a further proportion is partitioned towards harvestable products. Partial efficiencies (i.e. the ratio of nutrient output to nutrient input from and into each step) have been calculated much more commonly for the first and last steps than for manure handling and storage. However, nutrient losses during manure handling and storage may be substantial, depending on the type of management, so that these steps may represent either an open gate through which nutrients 'escape' the system or – if well managed – a safety net that can trap and retain nutrients within the crop-livestock system. In the case of N, estimates of partial cycling efficiency for each step ranged from 46 to 121% (livestock), 6 to 99% (manure collection), 37 to 85% (manure storage) and 3 to 76% (soil and crop conversion). Overall N cycling efficiency (NCE) is a product of the partial efficiencies at each of the steps through which N passes. Management strategies need to be designed to address efficient nutrient cycling within the entire system, rather than focusing just on partial efficiencies.

A farm-scale analytical framework is being developed which represents a farm livelihood system as a set of interacting components: the NUANCES (Nutrient Use in Animal and Cropping Systems: Efficiencies and Scales) framework (Giller et al., 2006). The framework combines participatory on-farm tools with dynamic databases and soil, crop, livestock and manure models. NUANCES is developed with the aim of embedding analyses of potential technologies within the wider livelihood strategies of farmers (see http://www.africanuances.nl). Few studies have compared the potential of many different options for soil fertility improvement or the ways that they can best be combined at farm scale. The components that are used to represent a farm livelihood within NUANCES are analysed using simple models of the sub-systems in the African context. The overall aim is to increase the understanding of the tactical and strategic decisions farmers make in allocating resources and the underlying trade-offs, where immediate needs of the family may often override the possibilities of investing in the longer-term sustainability of the farm. The approach is to use simple component sub-systems to avoid being overwhelmed by detail, but to include all relevant components to allow analysis of realistic scenarios (Fig. 1A). Fields are represented by the FIELD model that contains linked crop and soil models (Tittonell et al., 2007). Livestock feeding, milk, meat and manure production are represented by LIVSIM (Rufino et al., 2007a) and manure management by a new model, HEAPSIM, which we describe in this paper (Fig. 1B). The conceptualisation of HEAPSIM is based on the approach adopted by Rufino et al. (2006) to analyse on-farm mass and nutrient flows and capture the effect of management on resource use (in)efficiencies.

The objectives of this paper are: (i) to introduce the concepts and principles of nutrient cycling through livestock across different types of crop-livestock systems and how these concepts are simplified in HEAPSIM, the manure-management model of NUANCES; and (ii) to illustrate our approach by analysing N cycling efficiency through manure collection/handling and storage within smallholder crop-livestock systems of the Kenyan highlands. The calculations with the model use information on: (i) manure excreted and manure management collected from case-study smallholder farms in the

Kenyan Highlands; (ii) results of experimental work on manure mass, C and N losses during storage, complemented with data available from the literature to parameterise the model; and (iii) a fuzzy logic system to model the effect of management on manure losses during storage.

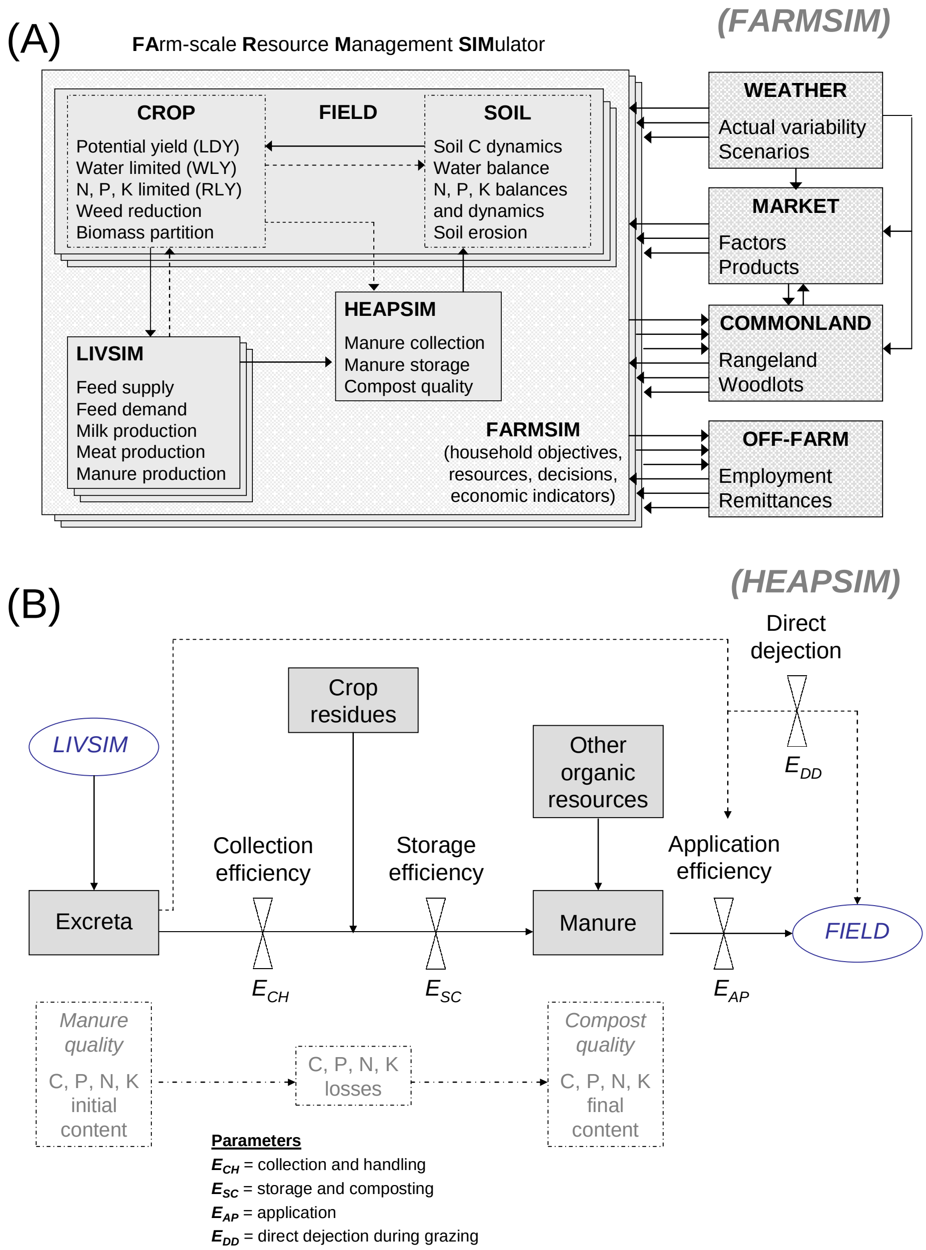


Figure 1: (A) A schematic representation of NUANCES-FARMSIM, the farm-scale modelling shell linking soil, crop, livestock and manure models and accounting for availability of farm-scale resources (such as cash and labour) and their dynamics throughout the year. (B) A diagram of HEAPSIM, the model for nutrient cycling efficiencies through manure management. In this diagram, the term manure refers to animal excreta, and compost to the final product after a period of storage. Four coefficients are defined that determine the efficiency of mass and nutrient retention at different stages between excretion and application to croplands, thus linking the models LIVSIM (LIVestock SIMulator) and FIELD (soil and crops).

# 2. Materials and methods

## 2.1 Model description

### *2.1.1 Mass losses during collection and storage*

The model simulates the effect on mass losses under alternative management strategies. Mass losses from manure are simulated using a simple dynamic approach in which two state variables are followed in time: manure in the stall ($M_{stall}$, in kg DM) and manure in the heap ($M_{heap}$, in kg DM). Nutrients flows are followed using the nutrient concentration at each state.

The monthly rate of change in manure in the stall is calculated as:

$$\frac{dM_{stall}}{dt} = M_{stall\_prod} - Losses_{stall} - Collection \,, \quad \text{(Eq. 1)}$$

where $M_{stall\_prod}$ (kg DM month$^{-1}$) is the amount of excreta that is voided by livestock. $Losses_{stall}$ (kg DM month$^{-1}$) represents the amount of manure that is lost, and $Collection$ (kg DM month$^{-1}$) is the amount of excreta that is being transferred to the heap. $M_{stall\_prod}$ is calculated as:

$$M_{stall\_prod} = M_{excreted} \times c_{partitioning} \,, \quad \text{(Eq. 2)}$$

where manure excretion ($M_{excreted}$, in kg DM month$^{-1}$) is an input to the model that can be either field data or data calculated by dynamic simulation using the model LIVSIM (Rufino et al., 2007a – Appendix 1). Management defines whether the urinary-N is lost or partially retained in the manure. When no or little bedding is used and the manure remains long in the stall, we assume that all urinary-N is lost. The coefficient of partitioning ($c_{partitioning}$) is a user-defined parameter which depends on the characteristics of the cattle feeding management, determined by the number of hours of free grazing, in relation to cropping seasons and feed availability. The rate of mass loss of manure from collection to storage ($Losses_{stall}$) is calculated as:

$$Losses_{stall} = M_{stall} \times RLF_{stall} \,, \quad \text{(Eq. 3)}$$

where $RLF_{stall}$ (month$^{-1}$) is the relative loss rate of manure dry matter before moving to the heap, determined by manure management. $RLF_{stall}$ needs to be derived from experimentation.

The monthly rate of change in mass for manure stored in a heap (or a pit) is calculated with the following equation:

$$\frac{dM_{heap}}{dt} = Collection - Losses_{heap} - Removal \ , \qquad \text{(Eq. 4)}$$

in which *Collection* (kg DM month$^{-1}$) is the amount of manure that is being transferred to the heap, *Losses* $_{heap}$ (kg DM month$^{-1}$) is the amount of mass that is lost from the heap (or pit), and *Removal* (kg DM month$^{-1}$) is the amount of manure that is removed from the heap to be applied in the fields after storage. The rate of mass loss from manure in the heap ($Losses_{heap}$) is calculated as:

$$Losses_{heap} = M_{heap} \times RLF_{heap} \ , \qquad \text{(Eq. 5)}$$

where $RLF_{heap}$ (month$^{-1}$) is the relative loss rate of dry matter from manure in the heap, determined also by manure management.

*2.1.2 Deriving parameters from field experiments and measurements*

The key parameters affecting nutrient cycling efficiencies in HEAPSIM are: the coefficient of partitioning, and the rates of loss of manure during collection and storage. We reviewed a number of studies conducted in Sub-Saharan Africa from which these parameters were determined.

*The coefficient of partitioning*

The coefficient of partitioning represents the fraction of total manure excreted that can be effectively collected for further use. The type of livestock production system determines the amount of manure that can be recycled within the farm. In the extensively managed farming systems of the Sahel, it was observed that the excretion rate during grazing is higher than that during resting/corralling (Fernández-Rivera et al., 1995; Schlecht et al., 2006) but when animals have access to feed (e.g., night grazing), feed intake and excretion events increase almost linearly with grazing time. Thus, the fraction of total manure produced that can be collected is related negatively to grazing time (Ayantunde et al., 2001) and can be expressed as $PC=1–0.042×GT$, where $PC$ is the partitioning coefficient and $GT$ is the grazing time in hours. In intensive farming systems of regions where human population pressure is high, grasslands are reduced in size or non-existent. The livestock feeding strategies determine the amount of collectable manure, since animals may stay partly in the stall, tethered on the homestead compound, grazing on roadsides, etc. An example of this type of system and the derivation of PC's from data collected in the field are presented in Section 2.3.1.

*Mass and nutrient losses in the stall ($RLF_{stall}$)*

Not all the nutrients from the collectable manure are recycled on-farm, even in zero-grazing stall-feeding systems. The largest C and N losses from manure occur within 7−10 days after excretion (Martins and Dewes, 1992; Murwira, 1995; Thomsen, 2000) and therefore the frequency of manure removal from the stall has a large influence on the amounts that may be further recycled. In intensive dairy systems manure may be removed daily from the stall, while in other, less intensively managed systems, such as semigrazing or free grazing, manure is collected from the corral once or twice a year just before application to the croplands. In the latter case, the overall losses from the collection/handling phase and the storage/composting phase can both be significant. In the first phase, decomposition begins when faeces, urine, feed refusals and bedding are mixed by trampling. By the time that manure is collected for composting (the second decomposition phase), significant mass and N losses may already have taken place. The use of bedding for stalled livestock helps to reduce N losses, because urine is absorbed and N is immobilised in the straw. Thus, the efficiency of N retention in the manure depends on the frequency of collection, on the use of bedding, and on the characteristics of the livestock housing (concrete floor, roofing).

We derived the relative loss factor for mass and N during the manure collection period from the experimental work of Lekasi et al. (2002; 2006) (Fig. 2A and B). Because these studies only reported losses after 60 days and no intermediate measurements were reported, we interpolated mass loss during the composting period using an exponential decay function assuming only one decomposition phase.

*Mass and nutrient losses during storage ($RLF_{heap}$)*

Across Sub-Saharan Africa (and also between different farms within a single village) there are farmers who actively manage manure for composting through frequent collection, turning, covering the heaps or keeping them under a roof, whereas others simply store manure in between cropping seasons, either heaping it pure or mixed with crop residues or throwing it into a pit together with household wastes, and also farmers who only collect manure from the corral for direct application to croplands just before planting. In some systems, particularly in semi-arid regions, manure is neither collected nor composted. Cattle graze the standing crop residues and void faeces and urine directly onto the croplands during the dry season. Such a diversity of systems implies a wide variation in nutrient cycling efficiencies.

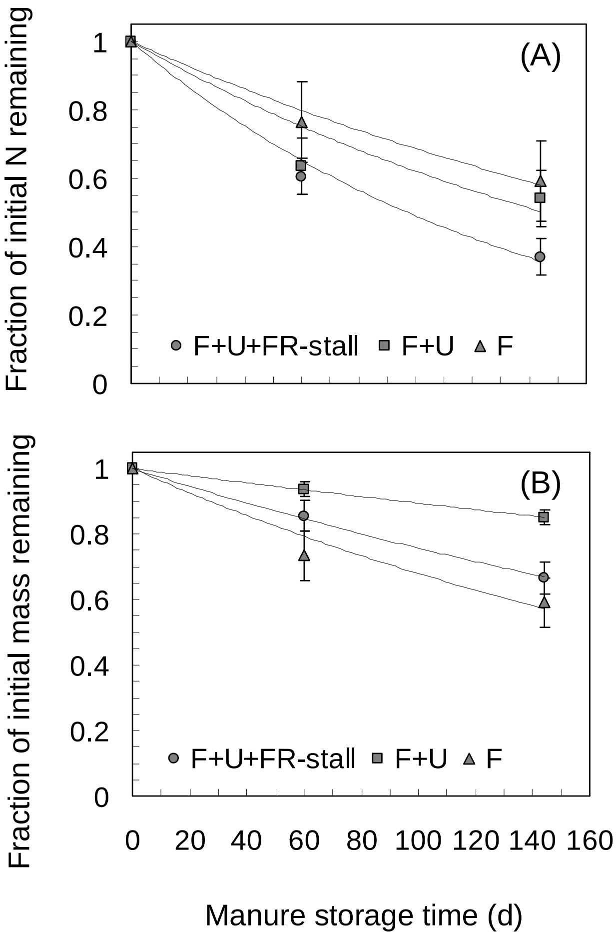


Figure 2: Nitrogen and mass remaining after decomposition of manure during manure handling (collection and storage) in systems where only faeces (F), faeces + urine (U), or faeces + urine + feed refusals (FR) are collected (after Lekasi et al., 2002; 2006). (A) Nitrogen remaining for further recycling, fitted functions: $y_{(F)} = e^{-0.0039x}$ , $r^2$=0.95 ($P$ < 0.05), $y_{(F+U)} = e^{-0.0011x}$ , $r^2$=0.99 ($P$ < 0.01), $y_{(F+U+FR)} = e^{-0.0028x}$ , $r^2$=0.99 ($P$ < 0.05). (B) Mass remaining (dry matter) for further recycling, fitted functions: $y_{(F)} = e^{-0.0038x}$, $r^2$=0.98 ($P$ < 0.05), $y_{(F+U)} = e^{-0.0048x}$ , $r^2$=0.84 ($P$ < 0.05), $y_{(F+U+FR)} = e^{-0.0071x}$ , $r^2$=0.99 ($P$ < 0.05).

The conditions under which storage takes place affect the rate of manure decomposition and the rate of nutrient losses through leaching and volatilisation. Aerobic storage results in faster C decomposition rates than anaerobic storage (Thomsen, 2000). Turning the material during composting (either in a heap or pit) accelerates the maturation process, but also increases C losses (Martins and Dewes, 1992). The size of the heap/pit also has an effect on the decomposition process because of the surface/volume relationship and the distribution of heat within the composting material. To quantify the effect of various factors affecting C dynamics and nutrient losses during manure storage and derive values of $RLF_{heap}$, we conducted a 7−month manure storage experiment (see Section 2.2).

*2.1.3 Deriving coefficients from 'expert knowledge': An application of fuzzy logic*

Fuzzy logic was chosen to describe the effect of manure management on mass losses throughout the storage/composting process because (i) it is easy to understand and to communicate, (ii) it is flexible and tolerant to imprecise data, (iii) it encompasses non-linearity and complexity – fuzzy systems can be created to match any set of input-output data, and (iv) the model can be built with expert knowledge. The theory of fuzzy sets relates to classes of objects with *un*sharp boundaries in which membership is a matter of degree. Real variables are translated into "linguistic" variables through the process of "fuzzification" (Von Altrock, 1995). The values of linguistic variables are expressed in words, rather than in numbers. Possible values of the linguistic variables are called terms or labels. For every linguistic variable, each label is defined by its membership function. For example, in manure management the variable 'roofing' may be given labels such as: no roof, wooden roof or iron-sheet roof. These are three different fuzzy sets that are ranked in a predefined scale, e.g., 0−10. For a particular case, the degree by which an object belongs to any of these fuzzy sets is denoted by a membership value ($\mu$). The membership function defines how each point in the input space is mapped to the membership value between 0 and 1. Thus, for the roofing variable there may be many intermediate situations such as, for example, partly unroofed ($\mu_{unroofed}$=0.25) and partly covered with a wooden roof ($\mu_{wood}$=0.33).
The next step or "fuzzy inference" is to determine the set of if-then rules that define the system behaviour and the values of the output linguistic variables. The fuzzy inference interprets the values of the input and, based on the set of rules, assigns values to the output. The *if* part of the rule combines conditions for all the variables by using a set of fuzzy logic operators (and, or, not). Each rule defines an action to be taken in the *then* part. With these rules fuzzy logic allows the user to distinguish between factors that are important and those that are less important. For example, the presence of a roof has a strong influence on how the management of the manure heap is evaluated. So two rules reflecting this strong influence are:

> '*if* roofing is <u>unroofed</u> *and* coverage is <u>uncovered</u> *and* floor is <u>sand</u>, *then* management is <u>very poor</u>'

and

> '*if* roofing is <u>roofed</u> *and* coverage is <u>uncovered</u> *and* floor is <u>not sand</u>, *then* management is <u>good</u>'.

For the calculation of the membership values of the output variables, the simplest approach has been taken (Von Altrock, 1995). If rules are defined alternatively, either rule A is true '*or*' rule B is true, in this case the maximum membership value (μ) is selected. When the logical operator '*and*' is used, the minimum membership value is selected.

The "defuzzification" step translates back the linguistic values into real values. The relationship between linguistic values and real values is given by the membership functions for the output variable. The shape of the membership function is defined with prior knowledge of the system under study. Most defuzzification methods use a two-step approach; in the first step a typical value is computed for each label in the linguistic variable, in the second step the best compromise is determined by balancing out the results, i.e., by finding the centroid of a two-dimensional function or a weighed average. To compute typical values of each label, the most common approach is to find the maximum of the respective membership function. The fuzzy system developed for the case studies analysed here is described in Section 2.3.2.

## 2.2 Manure storage experiment

We conducted an experiment to examine losses of mass, C and nitrogen under different manure storage conditions over 7 months at the experimental station of the National Agricultural Research Organisation at Kawanda, Central Uganda. The experimental design was a 2 × 2 factorial with coverage and roofing as treatments; manure heaps were either uncovered or tightly covered with a polythene film and the heaps were either unroofed (standing in the open air) or standing under a metal roof. These management practices reflect farmers' traditional and potential methods for manure storage in the East African Highlands. Roofed *vs* open air treatments were used to capture the effects of rain throughput and solar heating. A polythene film cover was used to prevent drying, reduce losses due to ammonia volatilisation and induce anaerobic conditions. Treatments were replicated three times and completely randomised.

The fresh manure was obtained from a large dairy farm and was relatively homogeneous. All heaps had similar initial size (339±11 kg fresh weight) and were periodically weighed and sampled. The manure in the heap was mixed each time sampling took place. While mixing we removed 100−200 g from each bucketful to get a bulk sample. This sample was mixed thoroughly, and four 100 g sub-samples were collected and refrigerated at 4°C prior to analysis of organic matter, total N, ammonia and nitrate using standard methods (Anderson and Ingram, 1993) at the Soil Science laboratory of the Makerere University in Kampala, Uganda. For estimating dry matter content, two of the samples were dried in the oven at 60°C to constant weight.

## 2.3 Application to case study farms in the East African highlands

### *2.3.1 Field data collection*

Case study farms were selected from the highly populated region of Vihiga district, western Kenya. The rainfall pattern in the area is bi-modal, allowing two cropping seasons a year (i.e., the long and the short rains). The human population density is high, and farm sizes are consequently small (average 0.5 ha). Farming is characterised by mixed crop-livestock systems, mainly annual crops with dairy cattle. Cattle are indicative of wealth and social status, and thus the number and type of cattle owned and their management varies widely not only across locations, but also between farms of different resource endowment. Farm households were selected purposively to represent the variability in resource endowment and cattle and manure management. Farmers were categorised according to their level of resource endowment, which has been observed to have a strong impact on manure management (Castellanos-Navarrete, 2007), into classes of high, medium and low: one case study farm corresponding to each class was selected for the model application. More details of the case studies and how the farmers were classified into wealth classes are given by Castellanos-Navarrete (2007).

Semi-structured interviews, resource flow maps, and direct sampling and analyses were used to collect data on (1) cattle management, including type of animal enclosure, roofing, floor type, drainage, use of bedding, cattle feeding system, and diet; (2) manure management, including manure handling and storage prior to utilization and the addition of urine and feed refusals to the manure heap/pit. For each farm, a sample of excreted, collected and composted manure was air dried and ground to pass through a 2 mm sieve. The manures were analysed for total and mineral N and C contents following standard methods (Anderson and Ingram, 1993). Based on daily observations and results of the chemical analyses, and on management information provided by the farmers, we estimated cattle diets and the flows of manure to the compost/storage heaps. The coefficients of partitioning were derived from the time spent by the cattle in the stall or grazing either on- or off-farm. Faeces and sometimes urine were collected only on-farm, mainly from the zero-grazing units, and from the stall where cattle overnight.

### *2.3.2 Model parameterisation and scenario analysis*

A simple fuzzy system was built to simulate the effect of management on manure storage ($E_{SC}$ in Fig. 1B) for the conditions of the East African Highlands. HEAPSIM is written in Matlab v. 7.0.4 (The Math Works, 2005). Three key linguistic variables were identified that account for the current management and also include possibilities for improved management: type of roofing (no roof, wooden roof and iron-sheet); type of coverage (no cover, branches, polythene film); and type of floor (sandy, solid, concrete) (Fig. 3A to C). The output of the fuzzy system, which is the result of a set of six rules (Box 1), is a management factor relating all management variables to values of mass losses from manure (Box 2) (Fig. 3D). The magnitude of the management factor (related to losses) used to translate back the linguistic variables were derived from Lekasi et al. (2002; 2006) (cf. Fig. 2), and from the results of the manure storage experiment and data collected at the case study farms in western Kenya.

Box 1: Rules regarding manure management in East African Highlands.

*if* roofing is unroofed *and* coverage is uncovered *and* floor is sand, *then* management is very poor
*if* roofing is unroofed *and* coverage is branches *and* floor is *not* sand, *then* management is poor
*if* coverage is uncovered *and* floor is *not* sand, *then* management is poor
*if* roofing is unroofed *and* coverage is polythene-film *and* floor is *not* sand, *then* management is good
*if* roofing is *not* unroofed *and* coverage is branches *and* floor is *not* sand, *then* management is good
*if* roofing is *not* unroofed *and* coverage is polythene-film *and* floor is *not* sand, *then* management is excellent

Box 2: Defuzzification of linguistic variables for manure management in the East African Highlands.

*if* management is very poor, *then* mass losses are very large
*if* management is poor, *then* mass losses are large
*if* management is good, *then* mass losses are small
*if* management is excellent, *then* mass losses are minimal

The rules that drive this fuzzy system imply that, with an uncovered heap, management will be either poor or very poor according to the type of flooring (Box 1). Improving the other factors and keeping the heap uncovered will not reduce significantly the mass and nutrient losses. To translate the values of the linguistic variables into a real value, first each rule is evaluated and the result is determined by implication by using the minimum method, which truncates the output fuzzy set. The value of the management factor is obtained by aggregation of the outputs fuzzy sets of each rule (Fig. 4). In this example, we used the maximum method for aggregation and the middle of the maximum method (the average of maximum value of the output set) to translate the value of the management factor into a real value (see Von Altrock, 1995).

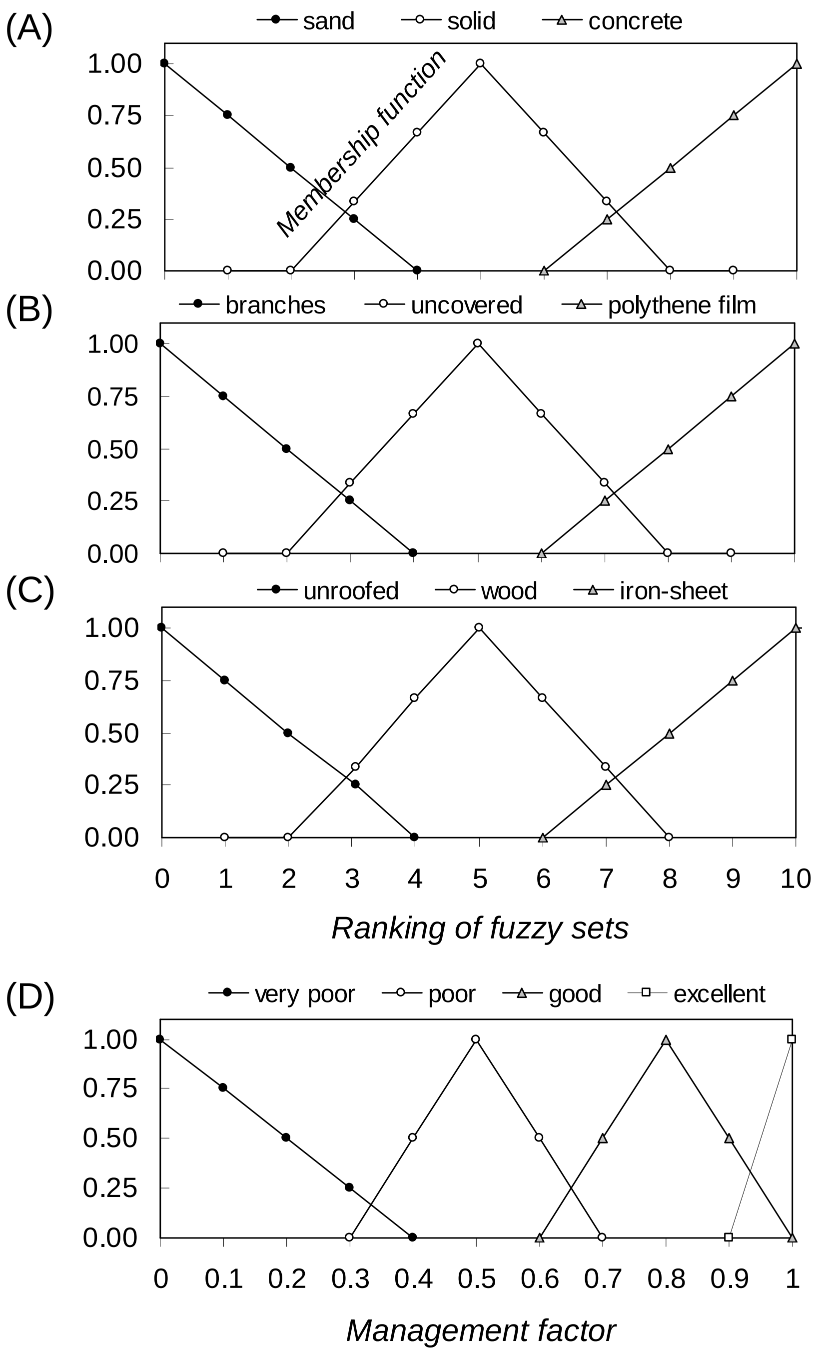


Figure 3: Fuzzy system for manure management. In the fuzzification process the management variables are converted into linguistic variables: type of roofing (A); type of cover (B); and type of floor (C). Membership functions are used to define to which degree an object belongs to the three different fuzzy sets. Here we used the simplest triangular membership function. For example, a rank value of 5 for the linguistic variable "type of roofing" implies a membership value of $\mu = 1$ for the "wood" fuzzy set, meaning that the object fully belongs to that particular fuzzy set. If the rank value of the linguistic variable is 3, then the object has a membership of 0.25 for unroofed and a membership of 0.33 for wooden roof, which can be interpreted as a heap that is partly unroofed and partly covered with a wooden roof. (D) Outputs are translated into a management factor in the defuzzification process. The linguistic variable "management factor" has four fuzzy sets: very poor, poor, good, and excellent management.

The management factor is then used to calculate the actual $RLF_{heap}$ as:

$$RLF_{heap} = Management\,Factor \times \left(RLF_{heap\,max} - RLF_{heap\,min}\right), \qquad \text{(Eq. 6)}$$

where $RLF_{heap\ max}$ indicates minimum mass losses that occur when management is near its optimum (heap is roofed, covered with plastic, and is lying on a solid floor), and $RLF_{heap\ min}$ captures the losses for the poorest manure management (unroofed, uncovered, sandy floor) for the system under study.

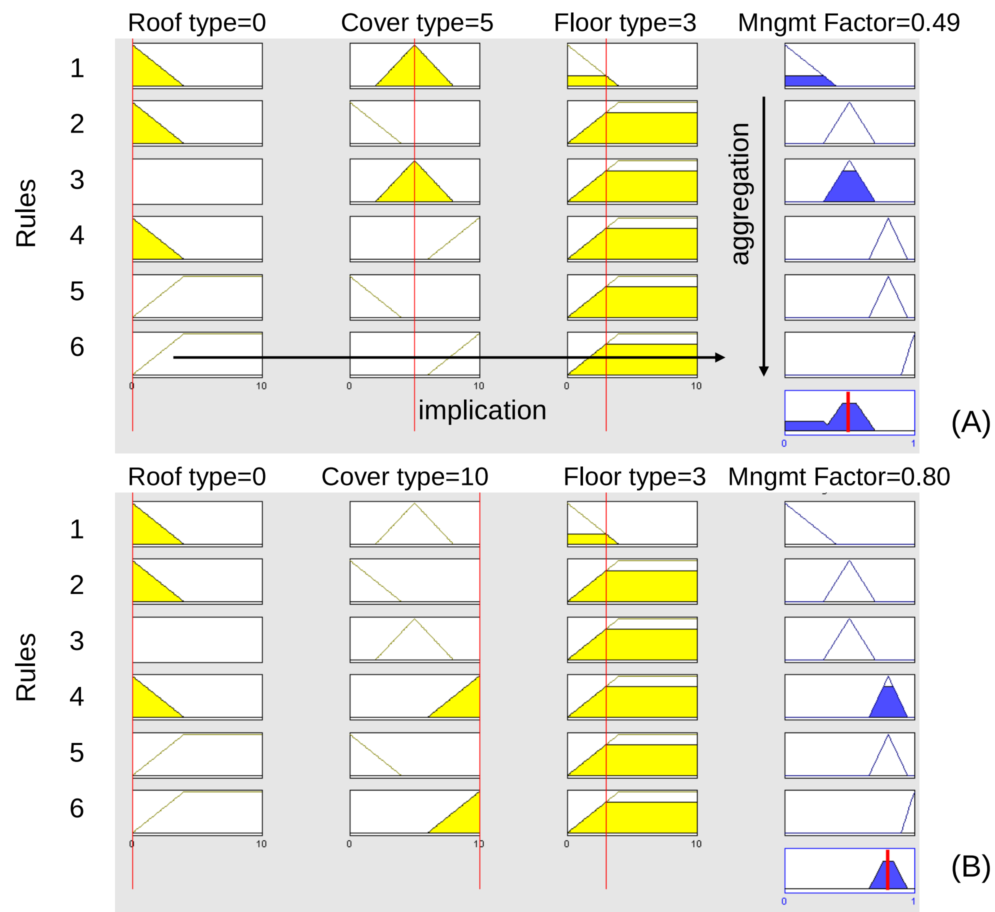


Figure 4. Diagram representing the fuzzy system for manure storage with three input variables (type of roofing, type of cover and type of flooring), six rules (cf. Box 1) and one output, the management factor. In the defuzzification process applied to the case study in Western Kenya, for which two scenarios of manure management were defined: (A) Scenario 1 with the current management, unroofed (roof=0), uncovered (cover=5) and solid floor (floor=3), management is poor; (B) Scenario 2 with improved management, unroofed (roof=0), polythene sheet as cover (cover=10) and solid floor (floor=3), management is good. The linguistic variables are translated back into real values. First each rule is evaluated; the minimum membership value of the three linguistic variables defines how the output fuzzy set is truncated. For scenario 1, only rules 1 and 3 determine the value of the output fuzzy set. For scenario 2, rule 4 has an effect on the shape of the output fuzzy set. The value of the management factor is obtained by aggregation of the outputs fuzzy sets of each rule by using the maximum method for aggregation and the middle of maximum method (the average of maximum value of the output set) to translate the value of the management factor into a real value.

With the described setting of the model, we performed runs for 2 years to evaluate the effect of manure management on the amount of N recyclable on-farm under two scenarios, current management and improved management, where mass losses are prevented by covering the heaps with a polythene film. We used monthly estimates of manure excreted and feed refusals addition (estimated to be 15% of the feed on offer) to the heap, together with the coefficient of partitioning to simulate manure decomposition.

# 3. Results

## 3.1 Mass and nutrient losses from stored manure

Covering the manure heaps with a polythene film had a stronger effect on mass and N losses than the presence of a roof (Fig. 5). The uncovered heaps underwent aerobic decomposition and lost about 55% of the initial dry mass and 50% of the initial N, whereas those that were covered and roofed lost about 30% of their mass and about 20% of their N during the 7 months of storage. Towards the end of the 7−month storage period, uncovered heaps had lost comparable amounts of mass and N irrespective of whether a roof was present. Initial larger losses of N than C explain the reduction in N concentration for most of the treatments (Table 1).

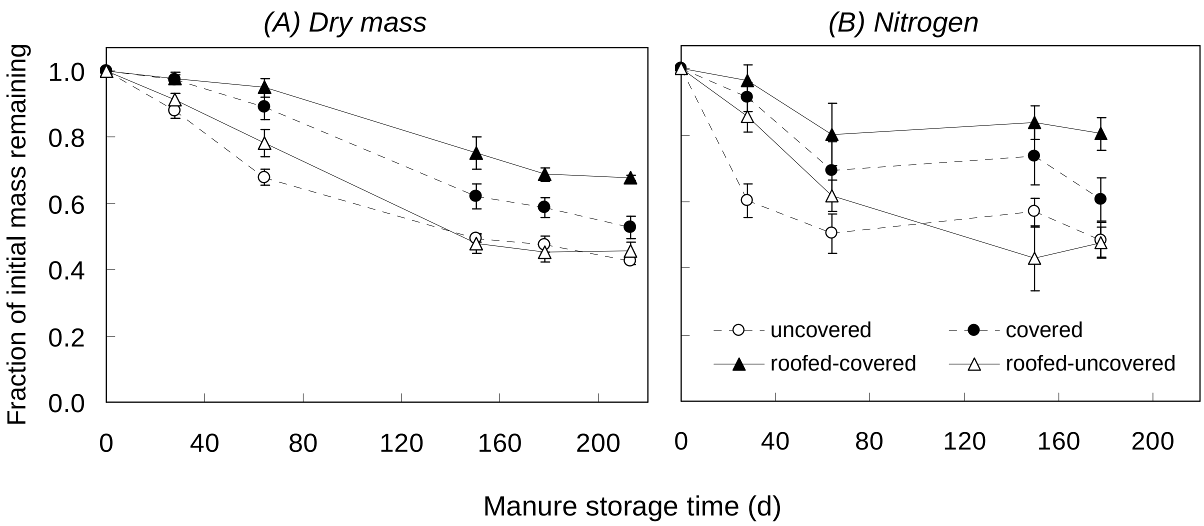


Figure 5. Mass and nitrogen remaining in manure heaps stored for 7 months under roof (roofed, solid lines) and in open air (unroofed, dashed lines), covered with a polythene film (covered, black symbols) or not (uncovered, white symbols), at Kawanda (central Uganda). (A) Fraction of mass remaining in the heap, (B) Fraction of N remaining in the heap. Bars show standard deviations.

Table 1: Characteristics of the manures under different management during storage in an experiment conducted at Kawanda, Central Uganda.

| Days of storage | DM (%) | Total N (%) | $NH_4$ (mg $kg^{-1}$) | $NO_3$ (mg $kg^{-1}$) | Org C (%) | C:N | DM (%) | Total N (% ) | $NH_4$ (mg $kg^{-1}$) | $NO_3$ (mg $kg^{-1}$) | Org C (%) | C:N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Unroofed-uncovered manure | | | | | | Unroofed-covered manure | | | | | |
| 0 | 25.0 ± 0.5* | 2.63 ± 0.19 | 2259 ± 149 | 4742 ± 418 | n.d. | n.d. | 25.2 ± 0.3 | 2.76 ± 0.51 | 2523 ± 378 | 4565 ± 727 | n.d. | n.d. |
| 27 | 29.8 ± 0.9 | 1.80 ± 0.10 | 2429 ± 269 | 503 ± 9 | 56.3 ± 0.2 | 31.4 ± 1.8 | 26.5 ± 0.3 | 2.57 ± 0.12 | 4065 ± 464 | 618 ± 78 | 56.4 ± 0.4 | 22.1 ± 1.1 |
| 63 | 35.1 ± 0.5 | 1.97 ± 0.27 | 93 ± 18 | 528 ± 24 | 53.4 ± 1.3 | 27.7 ± 3.7 | 26.6 ± 1.0 | 2.10 ± 0.10 | 166 ± 73 | 766 ± 35 | 57.6 ± 0.2 | 27.5 ± 1.2 |
| 149 | 27.4 ± 0.2 | 3.03 ± 0.26 | 9 ± 1 | 1020 ± 235 | 44.3 ± 0.6 | 14.7 ± 0.7 | 29.6 ± 0.6 | 3.20 ± 0.23 | 96 ± 6 | 1775 ± 52 | 44.6 ± 0.6 | 14.1 ± 1.0 |
| 178 | 31.3 ± 1.7 | 2.67 ± 0.23 | 119 ± 8 | 759 ± 90 | 30.2 ± 2.8 | 11.5 ± 1.6 | 30.4 ± 1.1 | 2.77 ± 0.26 | 183 ± 50 | 958 ± 36 | 25.9 ± 0.9 | 9.5 ± 0.8 |
| | Roofed-uncovered manure | | | | | | Roofed-covered manure | | | | | |
| 0 | 24.1 ± 0.8 | 2.43 ± 0.23 | 2526 ± 162 | 3743 ± 872 | n.d. | n.d. | 25.0 ± 0.1 | 2.33 ± 0.17 | 2343 ± 342 | 4141 ± 936 | n.d. | n.d. |
| 27 | 29.8 ± 0.6 | 2.37 ± 0.07 | 2177 ± 539 | 598 ± 63 | 56.5 ± 0.4 | 23.9 ± 0.7 | 26.0 ± 0.4 | 2.30 ± 0.10 | 3050 ± 504 | 592 ± 72 | 56.8 ± 0.2 | 24.8 ± 1.1 |
| 63 | 38.4 ± 1.4 | 1.93 ± 0.07 | 67 ± 11 | 644 ± 111 | 54.4 ± 0.3 | 28.2 ± 1.2 | 27.2 ± 0.8 | 1.96 ± 0.20 | 116 ± 28 | 735 ± 88 | 57.4 ± 0.8 | 29.8 ± 2.8 |
| 149 | 43.5 ± 0.9 | 2.28 ± 0.46 | 64 ± 30 | 1859 ± 83 | 33.2 ± 6.7 | 14.1 ± 0.1 | 28.0 ± 0.4 | 2.83 ± 0.23 | 97 ± 20 | 1806 ± 63 | 45.0 ± 1.6 | 16.2 ± 1.9 |
| 178 | 52.4 ± 1.2 | 2.52 ± 0.14 | 239 ± 53 | 982 ± 14 | 29.6 ± 4.1 | 11.6 ± 0.9 | 26.9 ± 0.5 | 2.72 ± 0.15 | 189 ± 56 | 929 ± 31 | 28.9 ± 4.6 | 10.5 ± 1.1 |

*s.e.m., *n* = 3;  n.d.: not determined

Because losses of C occurred gradually and continued throughout the storage period, a re-concentration of N was observed. At the end of the experiment, all treatments had similar C:N ratios. The results of the experiment showed that there is room for reducing mass and nutrient losses through simple and low-cost management interventions. The experimental results were used to calibrate the fuzzy logic system to predict mass losses during storage. The roofed-covered treatment was used as the best strategy, and therefore as the upper boundary for mass losses. The unroofed-uncovered treatment had the largest mass and N losses and represented the lower boundary.

## 3.2 Manure management in smallholder crop-livestock systems of western Kenya

In most farms visited during the field survey, farmers indicated that cattle were kept for milk production and/or for financial security, while manure was considered a by-product. The poorer farmers owned 1−2 head of local breeds of cattle (Table 2). Farmers in the wealthier category owned 3−6 heads and kept mostly dairy cows that were offered more and better quality feedstuff (a larger proportion of Napier grass in the diet as compared to maize stover), grazed less, and produced more manure. Farmers indicated feed scarcity as the main constraint to keep cattle. Fodder is often collected off-farm or bought when cash is available. Wealthier farmers and/or those more specialised in dairy farming kept the animals in a zero-grazing unit, while the others kept them tethered on the compound fields (on-farm), alongside roads or in public places (off-farm), or free-ranging (Table 2). This has direct consequences for the amount of manure that can be collected. Manure collection varies between the wet and dry season due to the varying feeding/grazing management. Manure excreted during night-stalling is usually collected each morning. Manure excreted during the day is lost when the cattle graze off-farm, and is partly collected when the cattle are tethered on-farm or kept within a zero-grazing unit.

Through repeated visits to the farms to weigh the manure during collection, we estimated that only around 40% of the faeces can be collected when the cattle are tethered on-farm. Most of the urine is lost, and only the urine collected in the night-stalling is sometimes further recycled. Most farmers accumulated the collected manure in a heap or pit together with feed refusals, and stored it between planting seasons. Manure is applied to crops prior to planting, and soon afterwards farmers start building a new heap (often in the same place) to be applied to crops in the next season. Therefore, fresh manure is continuously removed from the stall and added to the heap throughout the cropping seasons. Most farmers applied a fraction of the fresh manure directly to the fields. Estimates of the amounts of excreted manure, the estimated coefficient of partitioning (collectable manure), and the proportion collected and stored are reported for the selected case-study farms in Table 3. Variability in manure management was relatively smaller than the variability in feeding strategies. Most farmers stored the manure in an unroofed heap, uncovered or covered with branches, in a shaded area with a sandy/solid floor. For all farmers, the storage period was either 6 or 12 months, implying 1 or 2 applications to the fields each year.

Table 2: Main characteristics of the different wealth classes of a smallholders mixed farm system at Emuhaya division, Vihiga district, Western Kenya. The cattle feeding system (free-ranging, tethered (on or off-farm) and in a zero-grazing (ZG) unit) is expressed as a percentage of the total time spent by the cattle in a particular system per year. Diet composition is expressed as a percentage of the total dry matter of the diet (from Castellanos-Navarrete, 2007).

| Wealth class | Farm size (ha) | Crop-land (ha) | Cattle number | Cattle feeding system | | | | Diet composition | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Free-ranging (% year) | Tethered off-farm (% year) | Tethered on-farm (% year) | In the ZG unit (% year) | Napier grass (% diet) | Maize stover (% diet) | Other feeds[2] (% diet) |
| Poor | 0.1−0.8 | 0.1−0.7 | 1−2 | 0−35 | 0−21 | 36−90 | 0−29 | 10−35 | 27−69 | 16−38 |
| Medium | 0.4−1.1 | 0.3−1.0 | 1−5 | 0−16 | 0−29 | 0−84 | 0−100 | 14−36 | 44−74 | 12−24 |
| Wealthy | 0.7−1.2 | 0.6−1.1 | 3−6 | 0 | 0−4 | 0−43 | 43−100 | 51−66 | 10−21 | 13−39 |

[1] Cattle includes bulls, steers, cows, heifers and calves
[2] Other feeds are banana leaves and stems, local grasses, maize thinnings

### 3.3 Effect of management on mass and N losses

HEAPSIM was parameterised and run to represent the actual manure management observed in the case-study farms (Tables 3 and 4). We calibrated the model using data on composted manure from 10 farms and observed good agreement with the model predictions ($r^2$ > 0.9, root of the Mean Square Prediction Error = 130 kg DM $y^{-1}$). Differences in the production of fresh excreta were mainly caused by differences in herd composition (number, age, and size of the animals) and feeding management. The amount of manure stored depended, firstly, on whether the cattle grazed off-farm or on-farm, and, secondly, on the fate of the collected manure, which could be heaped or applied directly to the fields. The wealthier case-study farmer kept 2 small cows (170 and 190 kg) and a calf in a zero-grazing unit, collected most of the faeces daily, and added the material to an unroofed and uncovered compost heap. Adding organic residues to the heap was not a common practice on this farm. Mass losses of 53% during the 12–month storage period were simulated by HEAPSIM for this system (Fig. 6A). The case study farmer from the poorest category had one relatively large cow (360 kg) that spent most of the time tethered on-farm. Manure was collected daily from the compound ground, but a large proportion was lost. Around 60% of what was collected was added fresh directly to the fields, and the rest to the manure heap with little organic residues. The heap was predicted to lose 58% of its mass in the 12 months storage period (Fig. 6B). The farmer in the medium-class category had one relatively small cow (160 kg) that fed mostly on-farm, tethered on the compound. Manure was collected from the ground approximately every 3 days, and most of it (70%) was added together with crop residues and feed refusals to an unroofed manure pit covered with branches. The rest of the fresh manure was added directly to the fields. According to the model results, if no organic residues were added to the pit the manure mass loss would be ca. 60% (Fig. 6C). Addition of residues doubled the mass in the pit relative to the amount of manure added (Fig. 6D), and with smaller mass losses (42%).

Table 3: Management variables used to parameterise the HEAPSIM model for each of the wealth classes. Roof type, cover of the heap and floor type present a number between parentheses that corresponds to the management factor in the fuzzy logic system (cf. Figure 3A, B and C).

| Model inputs and parameters | Wealth class | | |
|---|---|---|---|
| | Poor | Medium | Wealthy |
| Faecal N (% DM) | 1.5 | 1.3 | 1.5 |
| Faeces excreted (kg DM $y^{-1}$) | 742 | 490 | 1502 |
| Manure after storage (kg DM $y^{-1}$) | 79 | 844 | 703 |
| Compost N (% DM) | 1.2 | 0.5 | 1.2 |
| Fraction collectable manure | 0.90 | 0.84 | 1.00 |
| Fraction collected manure | 0.58 | 0.76 | 0.80 |
| Fraction stored manure | 0.40 | 0.70 | 1.00 |
| Coefficient of partitioning[1] | 0.21 | 0.45 | 0.80 |
| Frequency of collection (d) | 1 | 3 | 1 |
| Duration of storage (mo) | 12 | 12 | 12 |
| Month of manure removal | February | February | February |
| Roof type | Unroofed (0) | Unroofed-wood (2) | Unroofed (0) |
| Cover of the heap | Uncovered (5) | Branches (0) | Uncovered (5) |
| Floor type | Sand-Solid (3) | Sand-Solid (3) | Solid (5) |

[1] Coefficient of partitioning = fraction collectable manure × fraction collected manure × fraction stored manure

For the poor farmer most N contained in the excreta was lost before collection, mainly because not all faeces are collected from the compound, and because no attempt was made to recycle urinary-N (Table 4). The wealthier farmer collected the faeces more efficiently, but did not recycle most of the urine. Calculated nitrogen cycling efficiencies (NCE) through collection (39−61%) and storage (34−51%) differed between farmer classes.

Table 4: Simulated mass and N losses under current manure collection and storage for three different wealth class farmers.

| Farmer | Faecal excreted N (kg N $y^{-1}$) | Faecal N lost before collection (kg N $y^{-1}$) | Urinary−N[1] (kg N $y^{-1}$) | NCE[2] collection | Fresh manure N applied to fields (kg N $y^{-1}$) |
|---|---|---|---|---|---|
| Poor | 11.1 | 5.3 | 3.8 | 0.39 | 3.5 |
| Medium | 6.9 | 2.5 | 1.9 | 0.50 | 1.3 |
| Wealthy | 22.5 | 4.5 | 7.2 | 0.61 | 0 |
| | Manure N added to heap (kg N $y^{-1}$) | Organic residue N added to heap (kg N $y^{-1}$) | Manure N after storage (kg N $y^{-1}$) | NCE storage[3] | NCE overall[4] |
| Poor | 2.3 | 0 | 0.8 | 0.34 | 0.13 |
| Medium | 3.1 | 4.8 | 4.9 | 0.51 | 0.25 |
| Wealthy | 18.0 | 0 | 8.4 | 0.47 | 0.28 |

[1] Estimations made with LIVSIM, urinary N is about 30% of the faecal N for this type of diet
[2] NCE collection = collected N / (Faecal N + Urinary-N)
[3] NCE storage = composted N / N added to the heap
[4] NCE overall = NCE collection × NCE storage

Table 5: Simulated mass and N losses with improved manure storage management: a polythene film is used to cover the heaps and heaps are placed in a solid floor.

| Farmer | Manure composted (kg DM $y^{-1}$) | Manure N after storage[1] (kg N $y^{-1}$) | NCE storage[2] | NCE overall[3] |
|---|---|---|---|---|
| Poor | 88 | 1.1 | 0.45 | 0.18 |
| Medium | 1268 | 6.3 | 0.65 | 0.33 |
| Wealthy | 970 | 11.6 | 0.65 | 0.39 |

[1] Here it was assumed that the N concentration of the composted manure did not increase compared with the composted materials in Table 4.
[2] NCE storage = composted N / N added to the heap
[3] NCE overall = NCE collection × NCE storage

The overall NCE for both manure collection and storage ranged from 13% for the poor farmer up to 28% for the wealthier farmer. Under the current management system, the manure storage management factor was similar for the three farmers (0.49 for the poorer, 0.63 for the medium and 0.50 for the wealthier farmer) because manure quality did not differ widely between farms. In the simulations with HEAPSIM we introduced a polythene film to cover the heaps to assess the effect on mass losses assuming that the N concentration of the end product does not change. The management factor increased to 0.8, 0.85 and 0.9, and the mass losses were reduced to 43, 25 and 35%, for the poorer, medium and wealthier farm, respectively. NCE through manure storage increased from 34−50% up to 45−65%, and the overall NCE from 13−28% to 18−39% (Table 5).

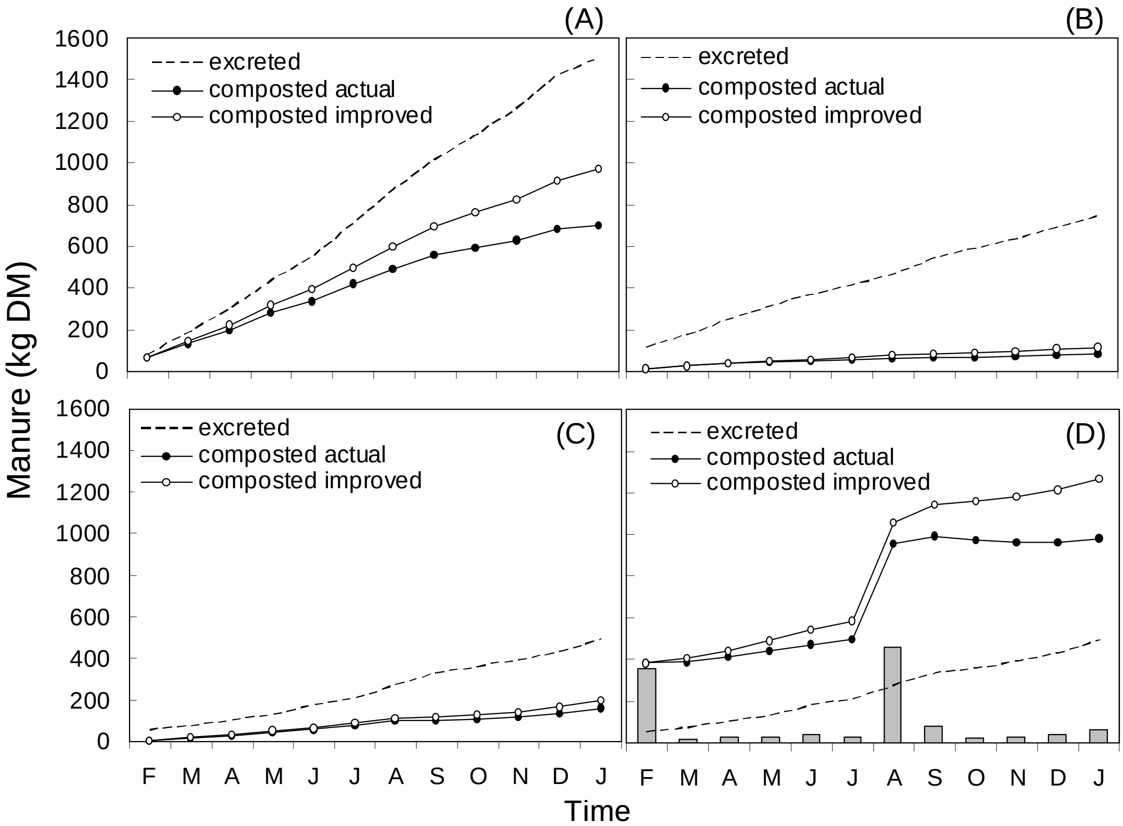


Figure 6: Cumulative mass of manure (kg DM) stored for 12 months as simulated by HEAP-SIM for the current scenario 'composted actual' and for the 'composted improved', in which manure is stored underneath a polythene sheet. The dotted line indicates the cumulative amount of excreted manure for (A) the wealthier farm, (B) the poor farm, (C) the medium farm if no organic residues were added; and (D) the medium farm with residues added. The bars in panel (D) indicate the amounts of organic residues added to the manure heap each month.

# 4. Discussion

## 4.1 Dry matter and nitrogen cycling efficiencies in smallholder farms

Manure management during collection and storage has a large effect on the efficiency of mass and nutrient retention within the farming system (Table 4). The differences in NCE between farmers of different wealth classes are mainly caused by differences in resource availability. For the poorer farmers large N losses occur at all stages of recycling (before and during collection, and during storage). The fact that cattle graze off-farm or are tethered off-farm reflects the opportunistic feeding strategy, which is probably a consequence of land (for forage production), cash and labour constraints. Substantial urinary-N losses were common to all farms, but their impact on NCE of the poor and medium class farms is larger due to the relatively smaller total amount of

N available for recycling, and because the cattle were fed on unbalanced diets that lead to excretion of a greater proportion of the N in urine than those provided with better quality feedstuffs. Farmers hardly make use of the urine, although in some cases urine may contain up to 50% of the N excreted by the cattle. N contained in the urine may be better captured within the system by collecting slurry (manure + urine) in a sump and then applying it directly to the crops, or by adding C-rich, fibrous bedding materials to the stall floor, so that the urinary-N is absorbed and immobilised. Similarly, direct application of plant materials to the soil may result in more efficient cycling of N, with fewer losses than from materials fed to livestock and applied as manure.

The current management practice allows the poor farmer to apply less than 1 kg N $y^{-1}$ of composted manure from the almost 15 kg N $y^{-1}$ excreted by the cattle (cf. Table 4). Improving manure storage does not help to increase the overall NCE significantly because of the large losses before storage. The addition of fresh manure to the fields may increase the NCE at farm scale. For the wealthier farmer, improvement of manure storage may result in noticeable increases in NCE and would allow recycling of about 30% of the N excreted by the cattle (about 30 kg $y^{-1}$) with a relatively small investment in storage and if urinary-N is utilised. Adding crop residues to the heap increases the volume of material that can be applied to the field, compensates directly for N losses from the faeces, and may also reduce ammonia volatilisation. On the other hand, addition of crop residues may increase the labour cost of handling and application because of the increased bulkiness of the composted material. Covering the manure heap with a polythene film reduced losses of mass and N in the experiment at Kawanda (Table 1, Fig. 2), suggesting that farmers may benefit from this low cost improvement of management.

This study showed a narrower range of NCE for the collection (39−61%) and storage (34−51%) than those reported earlier by Rufino et al. (2006). Opportunities for the poor farmer to increase the overall NCE require greater availability of feed on-farm, investment in cattle housing, and awareness of the usefulness of recycling of urinary-N. Improving the feeding of cattle and increasing cattle numbers would have a larger effect on manure available to crops, but feed scarcity at the larger scale, and cash constraints at farm scale, will impede that the poorest benefit from this strategy. The absolute amounts of N recycled (between 1−6, 4−17 and 7−18 kg N $y^{-1}$ for poor, medium and wealthier farmers) are small compared with the N demand of maize (>50 kg N $ha^{-1}$), but still significant. Application rates of 50 kg N $ha^{-1}$ are rarely realised by poor farmers who purchase only small quantities of fertiliser. The amounts of manure N recycled represented between 5−55 kg N $ha^{-1}$ $season^{-1}$ depending on farm sizes in the case study farms of 0.1−1.1 ha. Manure provides other important macro- and micronutrients to the crops and has a positive effect on maintaining (and sometimes increasing) soil organic matter, i.e., factors that are critical in ensuring the efficient use of mineral N fertilizers (De Ridder and Van Keulen, 1990; Giller, 2002). These are strong justifications to support the search for interventions that will help farmers to make a better use of animal manures. Although the absolute amounts of N that farmers may recycle with improved manure management have limited impact on crop productivity, manure is often the sole input available to farmers.

### 4.2 The modelling approach

HEAPSIM is simple and relatively easy to parameterise and adapt. The fuzzy logic system has been designed using the most important factors for manure management systems in western Kenya and may need adaptation for smallholder livestock systems in other regions. The factors chosen in our case are related to driving variables of C and N losses, such as temperature (volatilisation and denitrification losses) and rainfall (leaching and run-off). Other factors that can be translated into linguistic variables could be cumulative rainfall, or thermal time (degree-days) as proposed by Griffin and Honeycutt (2000), but the effects of these variables on the quantity and quality of manure needs to be tested in experiments. The shape of the membership functions was chosen arbitrarily. In the applications of fuzzy logic in industrial engineering, membership functions are mostly selected by trial and error. Here we chose the simplest membership functions, and as our understanding of manure management improves, such knowledge can easily be used to fine tune the fuzzy system.

Mass losses between excretion and collection were not included in the fuzzy logic model described here, and further development of the model could consider other key variables driving losses due to frequency of manure collection. Results from simple, low-cost experiments in combination with the objective judgment of experts (farmers, extension officers and scientists) are highly valuable to design fuzzy logic systems to quantify the effects of manure management. Further empirical research is required to understand the effects of current livestock management systems on nutrient cycling, for example to assess the effect of repeated (daily) addition of fresh cattle manure and plant materials to heaps during storage.

A potential weakness of HEAPSIM is the way manure decomposition is simulated. In the current version of the model, one organic pool of ‘uniform’ quality is recognised that decomposes at a constant rate. Attempts to simulate mineralisation of N from manures including several pools and quality parameters, such as C:N ratio, have been largely unsuccessful (e.g., Probert et al., 2005). Manures are chemically and physically different from plant materials as microbial decomposition takes place already in the rumen (Chesson, 1997), so that proximal analyses of fibre fractions in manures do not correspond to the same fractions in plant materials. Yang and Janssen (2000) proposed a mono-component model with a variable N mineralisation rate over time referred to as the speed of ageing of the substrate. The model of Yang and Janssen (2000) gave a goodness of fit higher than 0.9 for N mineralisation from farmyard manure. In the future development of HEAPSIM, we will test the usefulness of the mono-component approach with variable mineralisation rates.

## 5. Conclusions

The application of our modelling approach to the analysis of a smallholder farm in the highlands of western Kenya confirms the importance of manure management for N cycling efficiency at farm scale. A striking result of our analysis is the small quantities of N that are potentially recyclable through manure within the farm system (between 1 and 18 kg N $y^{-1}$ for our case studies). This supports the emerging consensus that mineral fertilizers are required to improve the productivity of smallholder farms (Smaling et al., 2006). Constraints to, and opportunities for improving nutrient cycling through manure should be considered within the wider context of the livelihood strategies of rural families. In the first place, because the capacity of farmers to invest labour and financial resources to improve manure management is limited, competing investments are more attractive (or more urgent) than investing in a good manure management system. Making the most efficient use of animal manures depends critically on improving manure handling and storage. A high frequency of manure collection from the housing facilities reduces mass and nutrient losses. Measures to improve manure handling and storage are generally easier to design and implement than measures to improve crop recovery of N, and need to receive greater attention if overall system N cycling efficiency is to be improved. Competing demands for cash and labour may prevent farmers from making better use of manures. Improving the feeding of cattle and increasing the number of cattle would have a larger effect on the amounts of manure available for crop production than improving manure management, but feed scarcity at the larger scale and cash constraints at farm scale will prevent the poorest farmers from benefiting from improved manure management. Nevertheless the contribution of organic matter and nutrients other than N, and the improved response of crops to mineral fertilisers in manure-amended soil, justify further attention to improving manure management in smallholder farms.

Chapter 4

# Lifetime productivity of dairy cows in smallholder farming systems of the highlands of East Africa[†]

[†] This chapter is under review as:
Rufino, M.C., M. Herrero, M.T. Van Wijk, L. Hemerik, N. de Ridder and K.E. Giller. Lifetime productivity of dairy cows in smallholder farming systems of the highlands of Eastern Africa. Submitted.

## Abstract

Evaluation of lifetime productivity is a sensible strategy to target interventions to improve productivity of smallholder dairy systems in the highlands of East African, because replacement decisions are normally not based on productive reasons. Feeding strategies and mortality may have long-term effects on productive (and therefore economic) performance of dairy systems. Because of the temporal scale needed to evaluate lifetime productivity (more than 10 years in dairy systems of the highlands of East Africa), experimentation with feedstuffs in single lactations is not enough to assess productive improvements. A dynamic modelling approach was used to explore the effect of feeding strategies on dairy cattle lifetime productivity, and to help identifying points where interventions may have a productive impact. We used LIVSIM-Cattle (LIVestock SIMulator), an individual-based, dynamic model in which production depends on genetic potential of the breed and feeding. We used as example the highlands of Central Kenya, and simulated individual animals throughout their lifetime using scenarios with different diets based on common feedstuffs used in these systems (Napier grass, maize stovers and dairy concentrates), with and without imposing random mortality rates to different age classes. The simulations showed that it is possible to target feeding to maximise lifetime productivity by supplementing concentrates to meet the nutritive requirements of cattle not only during lactation but also during early development to reduce age at first calving and extend productive lifetime. Avoiding undernutrition during the dry period by supplementing the diet with 0.5 kg of dairy concentrates helps to increase productivity and productive lifetime, but in practice farmers may not perceive immediate economical benefits because this practice results in a long term cumulative effect. Survival analyses indicated that non-supplemented diets prolong calving intervals. The simulations with imposed random mortality showed a reduction in productive life, number of calvings and therefore all other productivity indicators by about 43−65%. Selecting the best feeding strategies makes little sense when mortality of cattle may be as high as 15% per year. Reducing mortality by implementing health care management programmes must be included when designing interventions to increase dairy outputs because improving lifetime productivity has a larger impact on smallholders’ income than interventions targeted to improving daily milk yields through feeding strategies.

**Keywords:** Modelling, feeding strategies, cattle mortality, survival analysis, individual-based model

# 1. Introduction

Strategies of feeding, health care and culling are generally the main determinants for lifetime productivity of dairy cows. In high-input dairy systems, the culling policy is based mainly on unsatisfactory reproduction performance (i.e. failure to calve for 1−2 consecutive years) (Bagley, 1993). In these systems, milk production, number of calvings, numbers of calves weaned, and calf survival are traits related to lifetime productivity. Influence of health care and feeding are of little importance as these are under full control. In the context of smallholder dairy production in Sub-Saharan Africa, the evaluation of lifetime productivity of individual cows is more relevant than the short term productivity because it allows assessing long-term investment opportunities for farmers that have few animals and face difficulties to spread risk. Lifetime productivity needs to be maximised because of low replacement rates (Kebreab et al., 2005). Smallholders do not usually implement replacement policies, because cattle are considered valuable capital assets to the household and an important pathway out of poverty (Perry et al., 2002). In Sub-Saharan Africa, most smallholder farming systems are mixed crop-livestock systems, where production of feeds is highly variable in time in both quality and quantity (Powell and Williams, 1993). Crossbred dairy cattle have a productive life of about 5−8 years with three to five lactations (Mukasa-Mugerwa, 1989). Lifetime milk yields of 16,000 kg, five calves and a lifetime of ten years have been observed in Ghana for grade cattle (Kabuga and Agyemang, 1984) but normally lifetime yields are of about 9,400 kg in four to five lactations (Adeyene and Adebanjo, 1978). The main underlying cause of low productivity is undernutrition resulting from feed scarcity (Kebreab et al., 2005). Nutritional status and related growth rate and development define at which age heifers reach puberty (Bagley, 1993). Calving at an early age is a prerequisite to obtain maximum lifetime productivity (Osuji et al., 2005). Limited knowledge on the potential benefit from different feeding strategies prevents farmers from deciding how to feed cows according to their physiological status. Feed intake is therefore not optimised and production costs are not minimised. High calf mortality (ranging from 10 to 45%) and a lifetime production of 3−5 calves reduces the availability of females for replacements considerably (De Jong, 1996). The major challenge to maximise lifetime productivity is associated with the reproduction-nutrition interactions, and high mortality rates (Vargas et al., 2001).

Because many processes interact and the long time span that has to be investigated, experimentation can only partly help to asses the effect of management factors on the indicators of lifetime productivity. Modelling techniques are useful to summarise current knowledge, indentify gaps in knowledge and to capture the effect of multiple processes during a long time span. Dynamic models are useful tools to evaluate complex interactions and include farmers' decision-making. A considerable amount of effort has been allocated to study replacement decisions (Van Arendonk, 1985; Dijkhuizen et al., 1986; Sorensen, 1989), but there have been few studies on lifetime productivity in the tropics (Kahi et al., 2000; Ojango et al., 2005). There is a lack of simple tools to study this problem because existing models are too detailed and too demanding of input data. The objectives of this study were to quantify the effect of feeding strategies and mortality on the lifetime productivity of individual dairy cows using as an example the smallholder dairy systems of the Central highlands of Kenya to identify strategies to maximise the lifetime productivity. To achieve these objectives we used a dynamic individual-based model to simulate reproduction and production of cattle.

## 2. Materials and methods

### 2.1 The dairy systems in the Central Kenyan highlands

Smallholders produce around 80% of the total marketed milk in Kenya, where supply cannot yet meet the demand of the growing population. The Central Province has a relatively good access to the Nairobi market, which is the main market for farm products. In the last decades there has been a shift towards intensification of the dairy systems with stall fed zero-grazing and improved breeds. The large majority of households is engaged in agriculture and most have dairy activities as part of their livelihoods (Bebe et al., 2003b). Prolonged calving intervals are often the result of farmers extending the lactation period of their cows to sustain cash flows (Staal et al., 2001). Previous studies indicated that supplementation with concentrates is limited due to cash availability and that farmers feed on average only 1 kg concentrate animal$^{-1}$ d$^{-1}$ to lactating animals (Bebe, 2003). The most common feedstuffs are Napier grass (*Pennisetum purpureum* Schumach), dry maize stover and dairy concentrates. The main constraints to the production of dairy systems identified for Central Kenya are the seasonal fluctuations of feed, poor feed quality and labour shortages (Staal et al., 2001).

### 2.2 Model description and parameterisation

LIVSIM (Livestock Simulator), the model used in this study, is a dynamic model based on principles of production ecology (Van de Ven et al., 2003). Following these principles, LIVSIM simulates the performance of individual animals in time according to their genetic potential and feeding. Potential production is defined by mature weight, growth rate and milk yield. Figure 1 shows a flow diagram of the model.

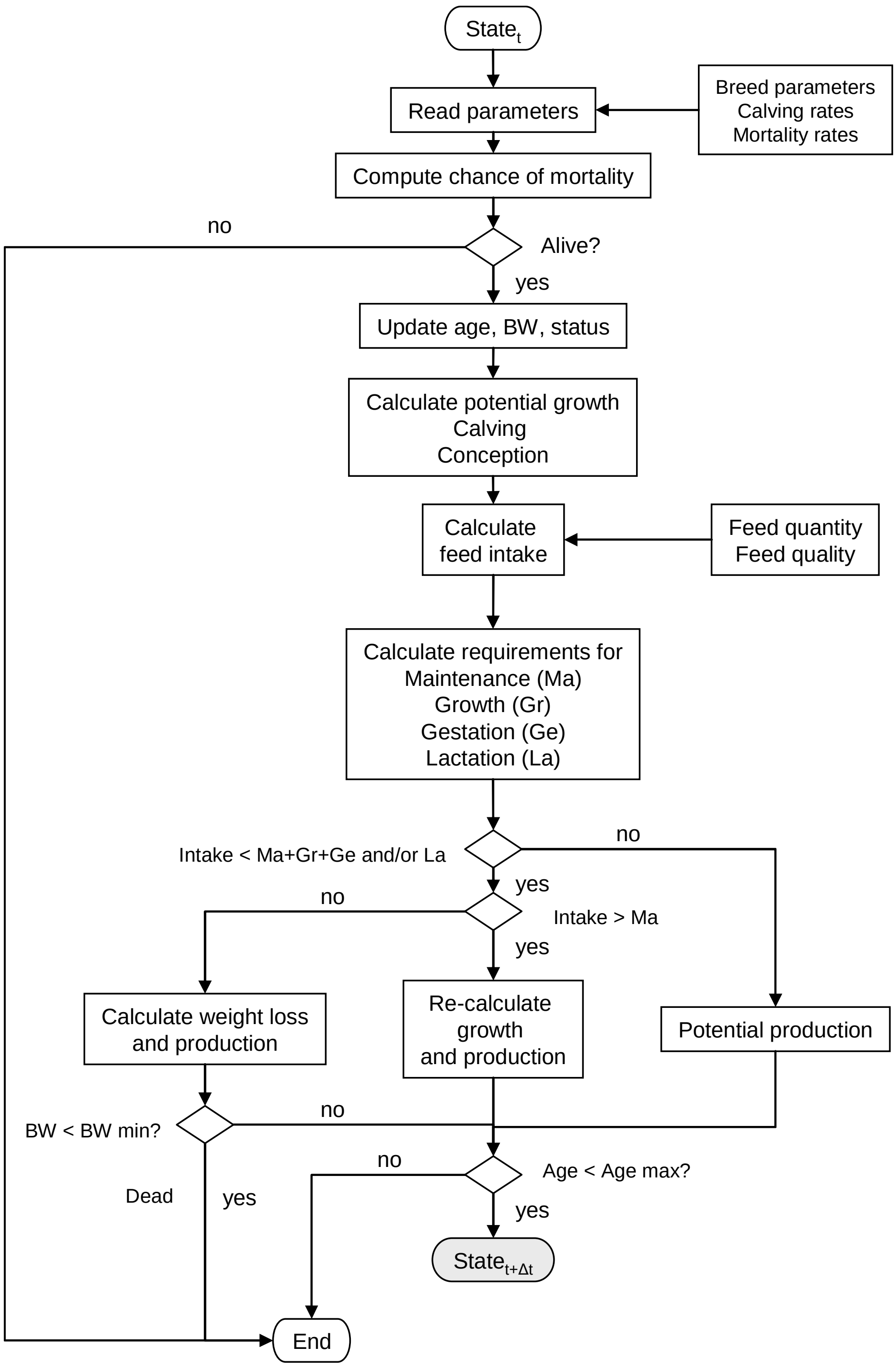


Figure 1: Flow diagram illustrating the structure of LIVSIM-cattle. Feed intake is compared with feed requirements for potential production. When these are not met, a set of priorities is used to partition energy and protein into lactation, gestation, growth and maintenance needs. Once production is calculated and if maximum age is not reached, and animals are not dead, a next time step (Statet+Δt) is simulated.

The model has been designed to evaluate the impact of the farmer's resource allocation on animal productivity. Because herds in such systems are usually small (2−3 animals), an individual-based model offers advantages above population models. Individual-based models (IBMs) allow the explicit inclusion of relatively short-term individual variation which is useful to explore life cycles in finer detail than the age-structure or stage-structure Leslie matrix models (DeAngelis and Mooij, 2005). When large herds are managed in feeding groups, dividing the population in classes may be more convenient than using individual-based models (i.e. Vargas et al., 2001).

In the model, the only discrete events that are triggered stochastically are conception, sex of the calves and random mortality (involuntary disposal). Mortality due to undernutrition, abortion, parturition, age and weight are described deterministically. Intake is driven by feed quality and bodyweight. Decision variables represent different management strategies related to feeding and reproduction. Reproductive performance is evaluated using a number of indicators: days to first conception, days open (days between calving and next conception), calving interval and length of the productive life (disposal date minus first calving date). Productivity is assessed with: number of offspring, milk production, weight gain and manure production. The model is written in MATLAB v.7.1 (The Math Works, 2005), the integration time-step is one month. The basic structure is based on the concepts of the model developed by Konandreas and Anderson (1982). LIVSIM differs from that model in (i) the nutritive requirements calculations which are based on AFRC (1993), (ii) feed intake which is based on the model of Conrad (1966), (iii) excreta production is estimated, and (iv) the decision variables. Potential growth is assumed to be a function of time, breed and sex. Potential growth and minimum bodyweight curves were derived by fitting a simplified Brody model (Brody, 1945) to data on bodyweight and age of Holstein-Friesian × Zebu cattle found in the literature. Compensatory growth is accounted for in the model by using different potential growth rates according to metabolisability of the feed (Tolkamp and Ketelaars, 1994). Conception is simulated stochastically by using probabilities associated to bodyweight and age combinations. We used the approach of Konandreas and Anderson (1982) and data from literature to determine a feasible age-bodyweight set when heifers achieve reproductive maturity. Calf birth weight is a breed-dependent input to the model. Milk yields are simulated by a breed-dependent potential milk yield which is a function of lactation length and in turn affected by age and a condition index of the cow. Lactation length and dry period are characteristics of the system under study and inputs to the model. It was assumed that calves are weaned at three months of age and that the milk allowance for calves starts with 4 L of milk per day when they are born up to 0.5 L per day when they are weaned. Mortality due to starvation is simulated using the growth routines taking the minimum bodyweight curve as threshold. Model inputs and model parameters are presented in Table 1. Individual components of the model were tested against experimental data from 24 cows obtained from Jenet et al. (2004a) for cross bred lactating cows fed different diets (Rufino et al., 2007a) – Appendix 1.

Table 1: LIVSIM model inputs and parameters.

| Parameters | Parameter value | Units |
|---|---|---|
| Mature weight | 500 | kg |
| Calf birth weight | 30 | kg |
| Weaning age | 4 | mo |
| Calving rate with poor condition | 0.35 | - |
| Calving rate with optimum condition | 0.90 | - |
| Mortality rate for calves up to 3 months | 0.15 | - |
| Mortality rate for cows from 2 to 6 years[1] | 0.07 | - |
| Mortality rate for cows from 7 to 13 years | 0.12 | - |
| Pregnancy length | 282 | d |
| Postpartum length | 2 | mo |
| Milk fat (average) | 35.4 | g $kg^{-1}$ |
| Milk crude protein | 32.0 | g $kg^{-1}$ |
| Milk metabolisable energy | 19.4 | MJ $(kg\ DM)^{-1}$ |
| Dry period | 2 | mo |
| Maximum milk yield | 4450 | kg $lactation^{-1}$ |
| Average maximum milk yield | 14.6 | kg $d^{-1}$ |
| Lactation length | 10 | mo |

[1] Mortality rates between age classes were calculated through linear interpolation

## 2.3 Running the model

For the simulations, each model run consisted of 13 years, considered to be the maximum lifetime of a dairy cow in the central highlands of Kenya (Bebe et al., 2003b). We used a monthly time step because the degree of detail suffices the purposes of our study and it will allow easy coupling to the farm-scale model NUANCES-FARMSIM (Giller et al., 2006). Because the model simulates discrete events by using stochastic variables, replications are needed to estimate the distribution of the output variables. We performed simulation experiments to evaluate the minimum number of simulation runs, i.e. replicates that capture the effect of the treatments. Model outputs were analysed with the Kruskal Wallis non-parametric test. Differences between simulations with different number of replicates were non-significant (*P*> 0.05), so that we decided to use 1000 replicates because there was no much gain in terms of the precision of the model outputs with higher numbers of replicates. Details on the calibration and testing of the model can be found in Rufino et al. (2007a) – Appendix 1. A number of variables and efficiency ratios were selected to evaluate lifetime productivity. Variables were: number of calves, milk production (kg lifetime$^{-1}$), days in milk (% lifetime$^{-1}$), days open (d parity$^{-1}$), cumulative gross income (KSh lifetime$^{-1}$)[‡], income from milk (KSh lifetime$^{-1}$), and income from animal sales (KSh lifetime$^{-1}$). Efficiency ratios were: cumulative milk per day open (kg dayopen$^{-1}$), total income per day open (KSh dayopen$^{-1}$), cumulative milk per day in milk (kg d in milk$^{-1}$), total income per day in milk (KSh d in milk$^{-1}$), days in milk in the lifetime (d lifetime$^{-1}$), milk in total lifetime (kg lifetime$^{-1}$), and income per day of lifetime (KSh d lifetime$^{-1}$).

## 2.4 Scenario analyses

To evaluate the relative impact of feeding management and mortality on the lifetime productivity of the cows we first analysed the effect of different diets on lifetime productivity (Scenario 1) and on reproductive performance (Scenario 2), and secondly the combined effect of diets and mortality on lifetime productivity (Scenario 3).

### *2.4.1 Scenario 1: Supplementing diets*

Supplementing the basal diet of lactating animals with concentrates at a rate of 2 kg per day during the entire lactation is the common recommended practice for the smallholder dairy systems in Kenya (Staal et al., 2001). Increasing the ration of concentrates during early lactation was recommended to increase milk yield of individual lactations (Kaitho et al., 2001). To test the effect of supplements on indicators of lifetime productivity, different rations of concentrates were used in model simulations to target different physiological stages. All females were offered a basal diet of Napier grass *ad libitum*. For all treatments ‘Napier+2kg’, ‘Napier+4kg’ and ‘Napier+8kg’ cows were supplemented with a total of 600 kg in 305 days of lactation, i.e. either 2 kg of concentrates d$^{-1}$ during the whole lactation period (0 to 305 days), 4 kg in early lactation (0−150 days), or 8 kg of concentrates d$^{-1}$ during only the first 75 days of the lactation. The quality of the feeds is shown in Table 2. Involuntary culling (random mortality) was set to zero to evaluate the sole effect of different diets.

[‡] Kenyan Shillings, 1 US$=67 KSh

Table 2: Quality parameters of different feedstuffs commonly used in the highlands of Kenya that were used in the model simulations. DM = dry matter; DMD = dry matter digestibility; ME = metabolisable energy; CP = crude protein; a = proportion of water soluble N in the total N in a feed; b = proportion of potentially degradable N other than water soluble N in the total N of the feed; c = fractional rumen degradation rate per hour of the b fraction of the feed N with time (AFRC, 1993).

| Feeds | DM ($g\ kg^{-1}$) | DMD ($g\ kg^{-1}$) | ME ($MJ\ kg\ DM^{-1}$) | CP ($g\ kg\ DM^{-1}$) | a ($kg\ N\ kg\ N^{-1}$) | b ($kg\ N\ kg\ N^{-1}$) | c ($kg\ N\ kg\ N\ h^{-1}$) |
|---|---|---|---|---|---|---|---|
| Napier grass [1] | 175 | 0.546 | 7.7 | 90 | 0.2 | 0.6 | 0.15 |
| Dairy meal [2] | 900 | 0.783 | 13.0 | 165 | 0.3 | 0.6 | 0.15 |
| Maize stover [3] | 850 | 0.540 | 6.8 | 54 | 0.3 | 0.5 | 0.07 |

References: [1] Muia (2000); [2] Abate and Abate (1991); [3] Methu et al. (2001)

### *2.4.2 Scenario 2: Diet composition and reproductive performance*

Increasing the number of lactations through improving nutrition has been suggested as one of the key interventions to improve productivity of smallholder dairies (Osuji et al., 2005). Feeding strategies that promote early body growth induce sexual maturity and result in a reduction of age at first calving and of the calving intervals (Bagley, 1993). Here we compared the effect of contrasting diets on age at first calving and calving intervals. To simplify the analysis we selected a number of diets that represents common practices in the Kenyan highlands. The first diet was Napier grass supplemented with maize stover finely chopped from January to March and from July to September (Napier+MS), when maize stover is available. The second diet was the same but with a fixed amount of 2 kg dairy concentrates per day being supplemented during the whole lactation (Napier+MS+2kg). The third diet was designed to meet the nutritive requirements by varying the amounts of supplemented concentrates according to the physiological stage of the animal (Napier+MS optimal). All these diets were compared with the sole Napier grass diet (Napier).

### *2.4.3 Scenario3: Lifetime productivity with random mortality*

Diets from the previous scenario were selected to evaluate the effect of actual mortality on indicators of lifetime productivity. Bebe et al. (2003b) reported for Central Kenya mortality rates for different age classes. Baseline mortality due to diseases is regarded as the main cause of animal disposal. Mortalities for the different age classes are reported in Table 1. By using random mortality rates we withdraw individuals from the simulated population that represent the dairy cow for which we evaluate lifetime productivity. For the analysis, it is assumed that every cow has the same probability per time step to be removed from the simulated population.

### 2.5 Statistical analyses

The effect of the treatments on indicators of lifetime productivity was evaluated with the non-parametric Kruskal-Wallis test and the differences between treatments were tested using the Wilcoxon-Mann-Whitney test. We report medians ($m$), means, ranges and probabilities. SPSS 15.0 for Windows (SPSS Inc., Chicago, IL) was used to perform the statistical analysis. The statistical technique called survival analysis was developed in medical sciences (Kleinbaum and Klein, 2005), where the event of interest was death. However, this technique can be used for analysing the timing of other events. We used survival analysis to evaluate the effect of treatments (diets and mortality) on age at first calving, calving intervals and productive life. Survival analysis was performed with R 2.6.0 (The R Foundation for Statistical Computing). Observations were censored when cows did not experience the event during the simulation. Kaplan-Meier (KM) survival functions were used for estimating survival times (Kleinbaum and Klein, 2005). From the survival curves, we estimated the median survival time at the point of the KM-curve with a cumulative survival probability of 0.5. Log-rank tests were used to compare age at first calving and productive life under different treatments (mortality rates).

Cox regression models were used for estimating the effects of covariates on the calving rate and therewith on the calving intervals. The Wald statistic ($z$) was used to test significance. The extended Cox model incorporates time-independent and time-dependent explanatory variables (Haccou and Hemerik, 1985). We used recurrent event survival analysis to assess the effect of relevant covariates on the calving event rate allowing for multiple events (calvings) per subject. A subject with more than one calving interval remains in the risk set until its last interval, after which the subject is removed from the risk set. The different observations of each individual are treated as independent contributions from different subjects. The hazard function is expressed as a function of time (Eq. 1).

$$h(t, X(t)) = h_o(t)\, e^{\left[\sum_{i=1}^{p_1} \beta_i X_i + \sum_{j=p_1+1}^{p_1+p_2} \delta_j X_j(t)\right]} \qquad \text{Eq. 1}$$

where $X(t)= (X_1,\ldots, X_{p1}, X_{p1+1}(t),\ldots, X_{p1+p2}(t))$ is a vector of explanatory variables, $\beta_i$ ($i$=1,…,$p_1$) is the regression coefficient for the time-independent explanatory variable $X_i$ , $\delta_j$ ($j$= $p_1$+1,…, $p_{1+}p_2$) is the regression coefficient for the time-dependent explanatory variable $X_j$. The explanatory variables were the diets taken as fixed factors, and the different components of the diet which were time dependent, and bodyweight was considered as confounder of the effect of the explanatory variable. When diets were considered as factors, the reference diet was the one that caused the longest calving interval. Maize stovers and concentrates were coded as factor variables and bodyweight was a continuous variable. The effect of the different diets is measured with the hazard ratio (*HR*) that describes how a baseline event rate is changed due to a change in the covariates $X_i$ (Eq. 2). The vector of covariates $X^*$ represents the group with largest hazard (i.e. shortest calving intervals) in order to facilitate the interpretation of the *HR*. A hazard ratio of 1 means no effect, a value of 10 means that one treatment has 10 times the hazard of the other treatment, in this case an increased risk of shortening calving intervals.

$$HR = \frac{h_0\left(t, X^*\right)}{h_0\left(t, X\right)} = e^{\sum_{i=1}^{p} \beta_i \left(X_i^* - X_i\right)} \qquad \text{(Eq. 2)}$$

# 3. Results

## 3.1 Diets and indicators of lifetime productivity (Scenario 1)

Supplementing the Napier grass diet with different amounts of concentrates throughout the lactation resulted in significant changes in all indicators of lifetime productivity (Table 3). Age at first calving was 3.6 y and equal for all diets. The 'Napier+4kg' diet resulted in the highest cumulative calvings (*m* = 7) and milk production (*m* = 22600 kg lifetime$^{-1}$), the most days in milk (*m* = 41% lifetime$^{-1}$), and the shortest average days open (*m* = 274 d parity$^{-1}$), as compared with the sole Napier diet. The number of calves obtained differed significantly between treatments: although the medians were the same the shape of the distribution of the populations was not normal and differed for each treatment. Simulations showed that both intake of metabolisable energy (ME) and crude protein (CP) were not matching the requirement for potential production during the entire lifetime (Fig. 2). In all feeding regimes, CP was in surplus during the dry periods. The 'Napier+4kg' diet resulted in higher production of milk because it met the energy nutritional requirements over time more closely than the other 3 diets. Although the diet supplemented with 8 kg of concentrates (Napier+8kg) allowed meeting nutritional requirements at peak lactation, it was still energy- and protein-deficient during the rest of the lactation.

Table 3: Effect of different diets on indicators of lifetime productivity. Diets consisted of Napier grass fed *ad libitum* supplemented with different amounts of concentrates during different stages of the lactation: 2 kg during 300 days (Napier+2kg), 4 kg during the first 150 days (Napier+4kg) and 8 kg during the first 75 days of the lactation (Napier+8kg). Medians and ranges between parentheses are shown for each of the indicators. Means are indicated for number of calves, next to the medians.

| | Napier | Napier+2 kg | Napier+4 kg | Napier+8 kg |
|---|---|---|---|---|
| Calves (# lifetime$^{-1}$)[1] | 6[d] (5.7) | 6[c] (5.9) | 7[a] (6.6) | 6[b] (6.4) |
| | (2−9) | (2−9) | (3−9) | (3−10) |
| Cumulative milk (kg lifetime$^{-1}$) | 13700[d] | 20000[c] | 22600[a] | 19700[b] |
| | (2300−18400) | (6900−27000) | (10700−31200) | (9700−29200) |
| Milk yield (kg lactation$^{-1}$) | 2500[d] | 3300[b] | 3500[a] | 3200[c] |
| | (800−2700) | (2400−3600) | (2700−3800) | (2600−3500) |
| Days in milk (% lifetime$^{-1}$) | 35[d] | 38[c] | 41[a] | 38[b] |
| | (12−57) | (13−55) | (19−57) | (19−63) |
| Days open (d parity$^{-1}$) | 365[a] | 340[b] | 274[d] | 284[c] |
| | (61−1354) | (132−983) | (110−983) | (97−983) |

[1] Different letters indicate significant differences ($P$<0.01) Mann-Whitney U test

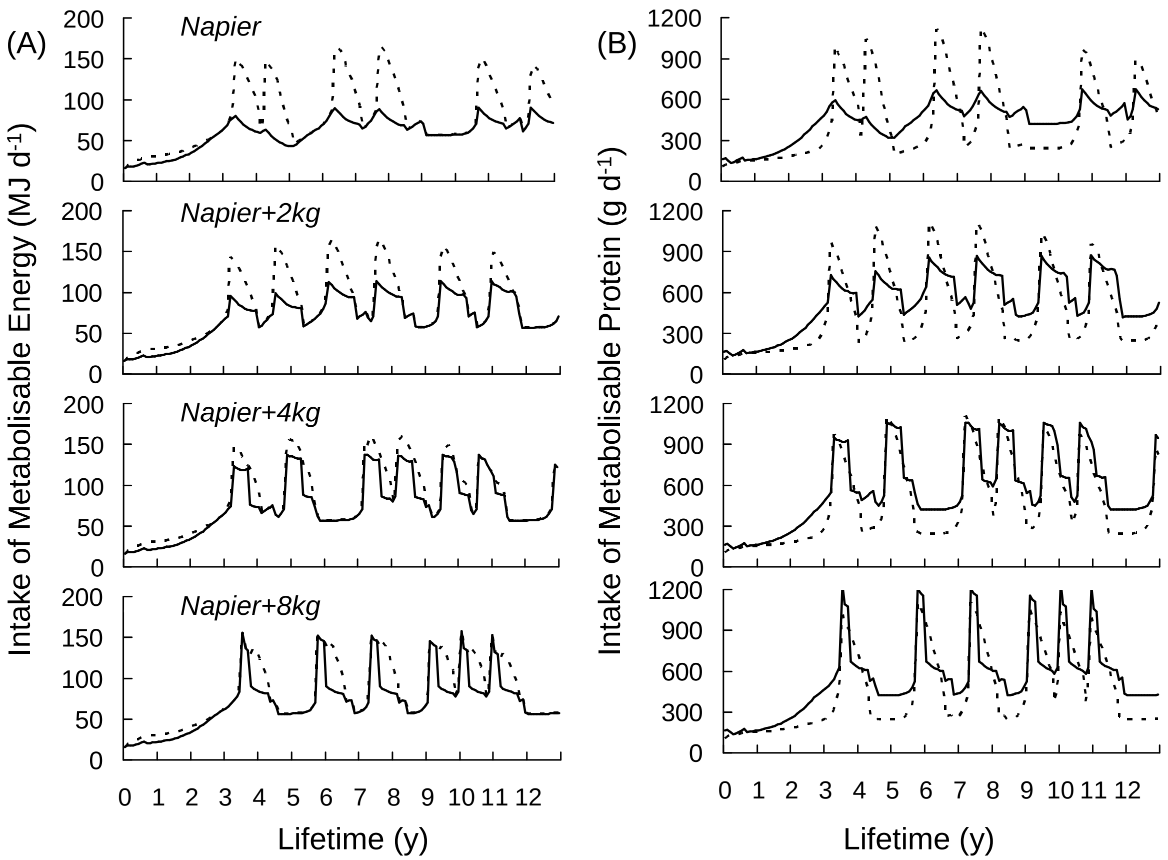


Figure 2: (A) Metabolisable energy (ME) requirements for potential production (dashed lines) and intake of ME (solid lines), (B) Metabolisable protein (MP) requirements for potential production (dashed lines) and intake of MP (solid lines). Diets consisted of Napier grass fed *ad libitum* without supplements (Napier) or supplemented with different amounts of concentrates: 2 kg during 305 days of lactation (Napier+2kg), 4 kg during the first 150 days of lactation (Napier+4kg), and 8 kg during the first 75 days of the lactation (Napier+8 kg).

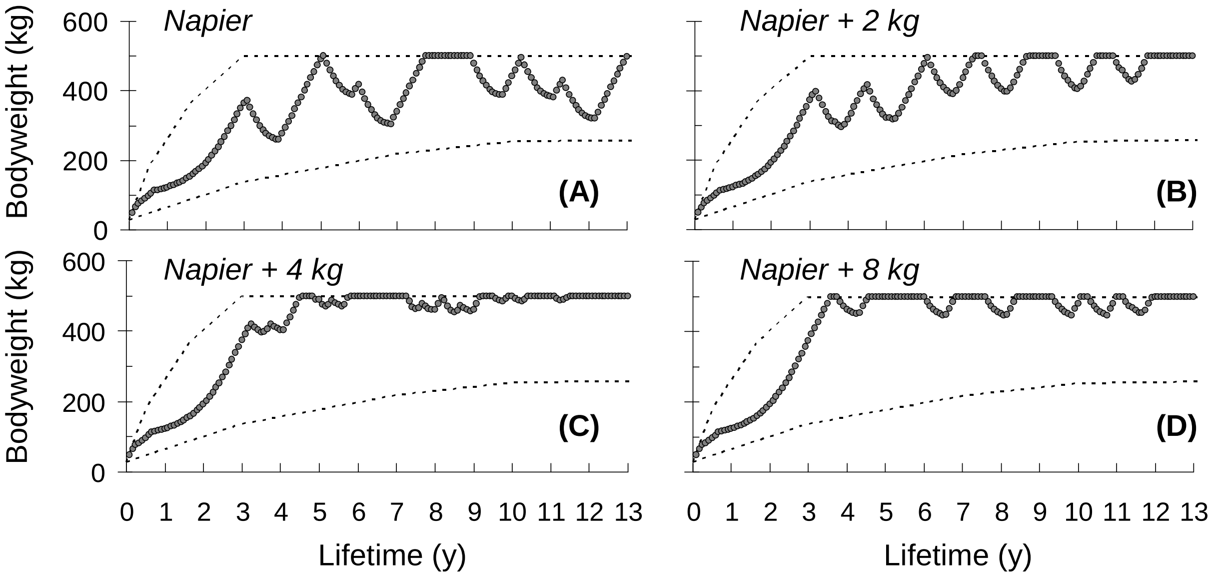


Figure 3: Development of a cow's bodyweight fed different diets: (A) Sole Napier grass (Napier), (B) Napier grass supplemented with 2 kg concentrate per day during the 305 days of lactation, (C) Napier grass supplemented with 4 kg concentrate during the first 150 days of lactation, and (D) Napier grass supplemented with 8 kg concentrate during the first 75 days of lactation. The upper dashed line shows the potential growth curve and the lower dashed line the minimum bodyweight for the breed.

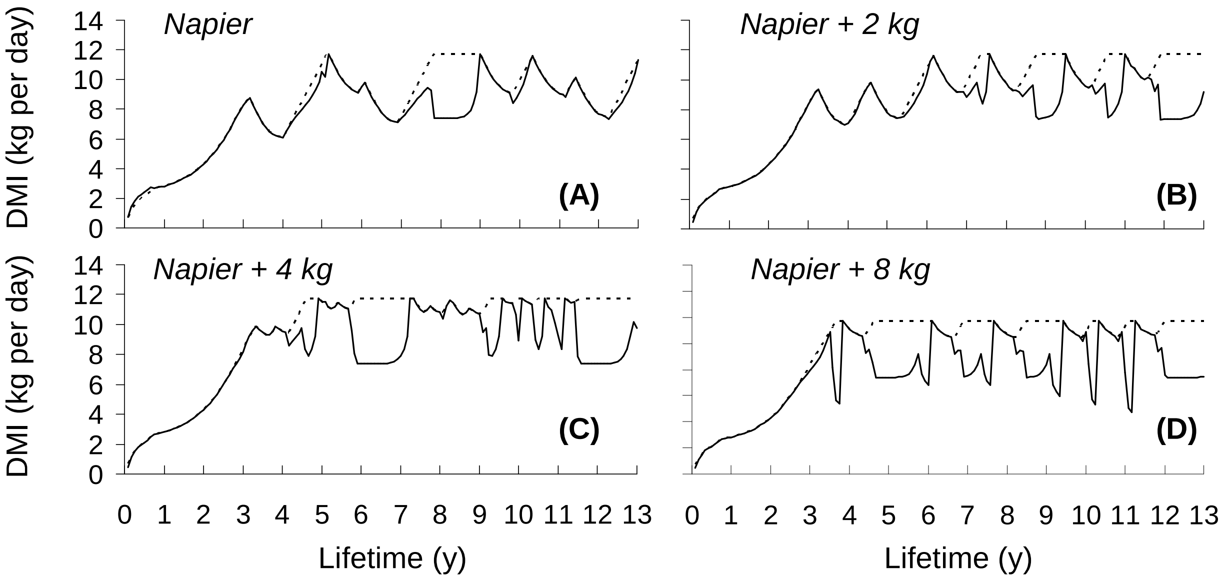


Figure 4: Daily intake of forage dry matter (DMI) for cows fed different diets: (A) Sole Napier grass (Napier), (B) Napier grass supplemented with 2 kg concentrate per day during the whole lactation, (C) Napier grass diet supplemented with 4 kg concentrate during the first 150 days of the lactation, and (D) Napier grass diet supplemented with 8 kg concentrate during the first 75 days of the lactation. Dashed lines show the potential dry matter intake and solid lines actual intake.

The 'Napier' and the 'Napier+2 kg' diets resulted in large losses in bodyweight after calving because of the large amount of energy and protein needed for milk production. These losses were less evident for the 'Napier+4kg' and 'Napier+8kg' diets (see for example Fig. 3). Cows could potentially eat a maximum of about 12 (kg DM) $d^{-1}$ of Napier grass of the quality used in the simulations (Table 2). During early lactation, the over-supply of ME for the latter two diets depressed grass intake (see for example Fig. 4). Because total dry matter intake was increased as the supplements of better quality were all consumed, it resulted in significant differences ($P$<0.01) in forage consumption between diets. Cows fed the 'Napier+4kg' diet consumed the largest amount of forage and concentrate (39.4 and 4.7 t lifetime$^{-1}$ of grass and concentrates, respectively) and cows fed the 'Napier' diet consumed the least (37.4 and <0.1 t lifetime$^{-1}$ of forage and concentrates, respectively).

### 3.2 Reproductive performance and lifetime productivity (Scenario 2)

We designed an 'optimal' diet that followed the cow's energy requirements more closely. This diet consisted of Napier grass with small amounts of concentrates (0.5 kg per day) during early phases of the calf and heifer development, 5 kg during the first 150 days of lactation and 1 kg during the rest of the lactation. The Kaplan-Meier survival curves and long-rank tests showed that the diets had a significant effect ($P$<0.01) on age at first calving (Fig. 5A).

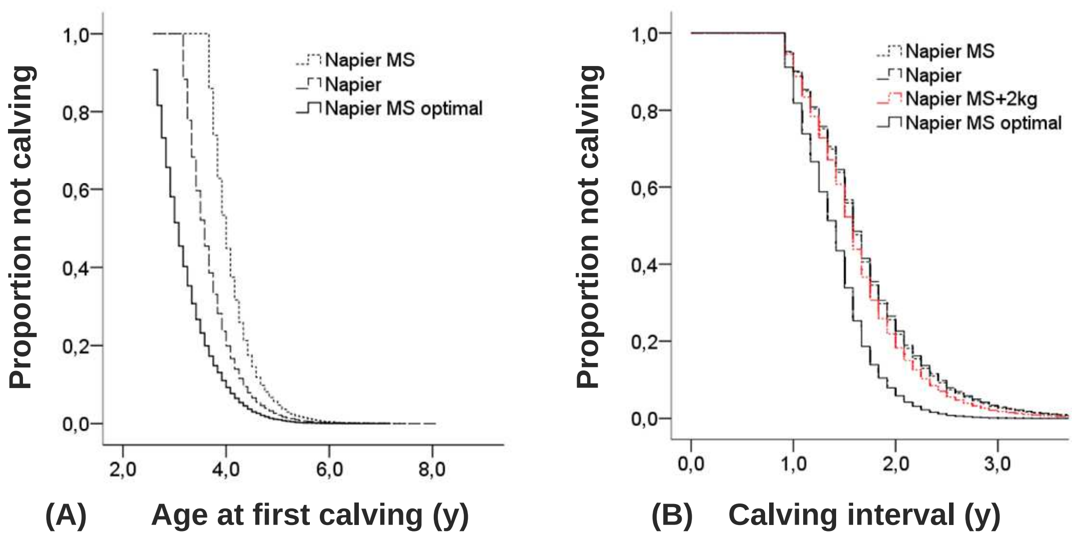


Figure 5: Kaplan-Meier survival curves for: (A) Age at first calving of cows fed 3 different diets: sole Napier grass, Napier grass supplemented with maize stover (Napier MS), and Napier grass supplemented with 0.5 kg concentrates per day except during early lactation (5 kg) and late lactation (1 kg) (Napier MS optimal), and (B) Calving intervals for cows fed 4 diets, the same as in (A) plus Napier grass supplemented with maize stover and 2 kg of concentrates during the whole lactation (Napier+MS+2kg).

Age at first calving was 3.08±0.01 y for the 'Optimal' diet, 3.58±0.01 y for the 'Napier' diet, and 4.0±0.01 y for the 'Napier+MS' diet. The 'Napier+MS+2kg' diet was not included in the Kaplan-Meier curve for the age at first calving because the effect on age at first calving was similar to the 'Napier+MS' diet since supplementation started only after first calving. The supplemented diets, 'Napier+MS+2kg' and 'Optimal', had a significant ($P$<0.01) effect on reducing the calving intervals compared with the 'Napier+MS' diet. Calving intervals, which excluded age at first calving were 1.17±0.01 y, 1.58±0.01 y for the 'Optimal' and the 'Napier+MS+2kg' diets, respectively, and 1.67±0.01 y for the 'Napier' and 'Napier+MS' diets (Fig. 5B).

Diet had a direct effect on productive life span, with 9.92±0.01 y, 9.42±0.01 y and 8.92±0.01 y for 'Optimal', 'Napier' and 'Napier+MS' diets, respectively. The seasonal addition of maize stover to the basal Napier grass diet reduced productive life of the cows and had an effect in all indicators of lifetime productivity (Table 4). In general, this effect is more pronounced for non-supplemented diets due to energy deficits during the lactation periods. Milk production was greatly affected, with an average reduction of 600−1400 kg of milk per lactation when comparing the sole Napier and supplemented diets. Days open were smallest for the 'Optimal' diet ($m$ = 240 d parity$^{-1}$), followed by the 'Napier+MS+2kg' ($m$ = 335 d parity$^{-1}$), 'Napier+MS' ($m$ = 345 d parity$^{-1}$), and finally 'Napier' ($m$ = 365 d parity$^{-1}$) diets. Adding concentrates to the diet consisting of Napier grass and Napier grass plus maize stover improved ($P$<0.01) cumulative milk yield considerably, by about 60% for the 'Napier+MS+2kg' diet and more than 100% for the 'Optimal' diet.

Table 4: Effect of diet on indicators of lifetime productivity. The diet consisted of Napier grass (Napier), Napier grass supplemented with maize stover (MS) 6 months per year (Napier+MS), Napier grass, maize stover plus 2 kg concentrates during the whole lactation (Napier+MS+2 kg), and Napier grass, maize stover supplemented with 0.5 kg concentrates except during early lactation (5 kg) and late lactation (1 kg), named the Optimal diet. Medians and ranges between parentheses are shown for each of the indicators. Means are indicated for number of calves, next to the medians.

| | Napier | Napier+MS | Napier+MS+2 kg | Optimal |
|---|---|---|---|---|
| Calves (# lifetime$^{-1}$)[1] | 6$^{b}$ (5.7) | 6$^{d}$ (5.2) | 6$^{c}$ (5.6) | 7$^{a}$ (7.3) |
| | (2−9) | (1−9) | (2−9) | (3−10) |
| Cumulative milk (kg lifetime$^{-1}$) | 13700$^{d}$ | 10700$^{c}$ | 17000$^{b}$ | 25400$^{a}$ |
| | (2300−18400) | (900−15000) | (6500−23000) | (11400−35400) |
| Milk yield (kg lactation$^{-1}$) | 2500$^{c}$ | 2100$^{d}$ | 3100$^{b}$ | 3500$^{a}$ |
| | (800−2700) | (500−2600) | (2100−3500) | (3000−3800) |
| Days in milk (% lifetime$^{-1}$) | 35$^{b}$ | 32$^{d}$ | 35$^{c}$ | 45$^{a}$ |
| | (12−57) | (13−55) | (13−54) | (19−63) |
| Days open (d parity$^{-1}$) | 365$^{d}$ | 345$^{c}$ | 335$^{b}$ | 240$^{a}$ |
| | (61−1354) | (61−1278) | (163−1460) | (88−882) |

[1] Different letters indicate significant differences ($P$<0.01) Mann-Whitney U test

The 'Napier+MS' diet was used as baseline for a Cox regression analysis because it resulted in the oldest age at first calving and the smallest number of calves per lifetime. In the first Cox model, diets were considered fixed factors, i.e. the other 3 diets were compared with the reference diet. The results of the regression analysis showed that all the diets had a significant effect ($P$<0.01) on reducing calving intervals after adjusting for bodyweight (Table 5). The hazard ratios indicated that the diets shortened calving intervals with respect to the 'Napier+MS' diet when there was at least an average difference of inter-calving bodyweight of 46 kg for the 'Napier' diet, 17 kg for the 'Napier+MS+2kg' diet and 64 kg for the 'Optimal' diet. These differences in bodyweight were observed for all treatments as shown for example in Fig. 6.

Table 5: Effects of the diets as fixed factors on calving intervals estimated with an extended Cox model.

| Explanatory variables | Coef. | s.e. | Hazard ratio | 95% Conf. interval | | Wald statistics (z) |
|---|---|---|---|---|---|---|
| Diet 1 (Napier diet) | −0.279 | 0.028 | 0.756 | 0.716 | 0.798 | −10.1*** |
| Diet 2 (Napier+MS+2kg diet) | −0.100 | 0.027 | 0.904 | 0.858 | 0.953 | −3.7*** |
| Diet 3 (Optimal diet) | −0.384 | 0.030 | 0.681 | 0.642 | 0.722 | −12.91*** |
| Bodyweight | 0.006 | 0.000 | 1.006 | 1.006 | 1.007 | 38.12*** |

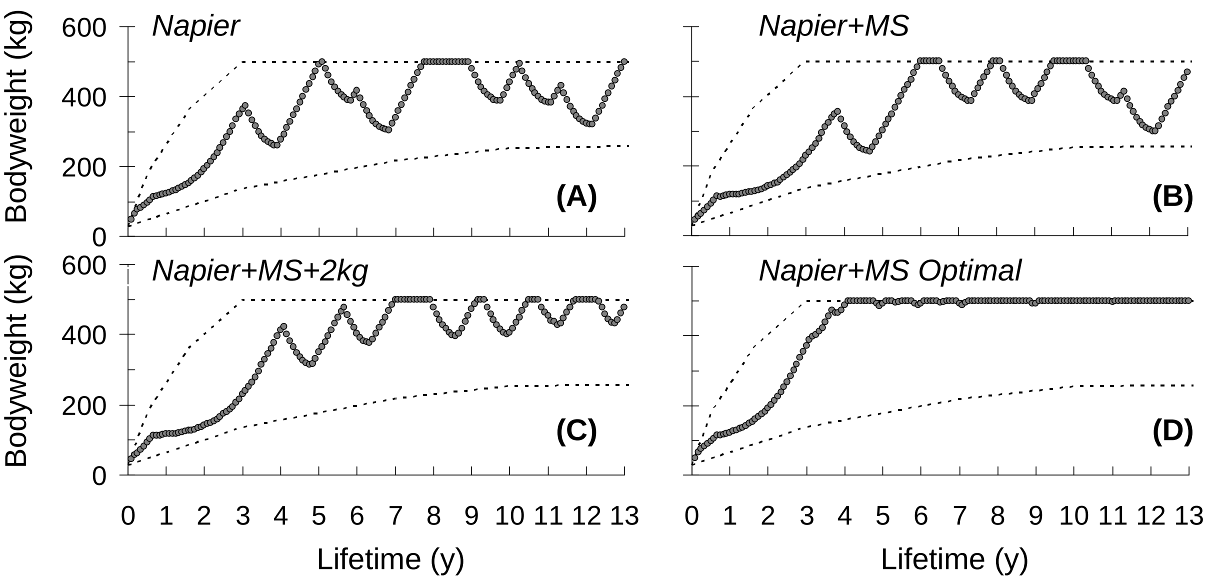


Figure 6: Development of the cow's bodyweight when fed: (A) Sole Napier grass (Napier), (B) Napier grass supplemented seasonally with maize stover, (C) Napier grass supplemented maize stover and 2 kg concentrate per day during the whole lactation, and (D) Napier grass supplemented with 5 kg concentrate during the first 150 days of the lactation and 1 kg per day the remaining of the lactation. The upper dashed line shows the potential growth curve and the lower dashed line the minimum bodyweight for the breed.

Because the effect of the diets is time dependent, we looked at the separate effect of the seasonal supplementation with maize stover and the supplementation with different amounts of concentrate during early lactation − where the largest losses of bodyweight usually occur. The hazard functions for each of the diets are shown in Table 6. All coefficients shown were significant ($P$<0.01). The addition of maize stovers (MS) to the diets tends to increase calving intervals by halving the hazard rate. This effect is outweighed by supplementing concentrates as shown by the coefficients $\beta_2$ in Table 6, which differ between the 'Napier+MS+2kg' and 'Optimal' diets. At the same bodyweight difference caused by the diets, the 'Napier+MS+2kg' diet would result in the shortest calving interval but from Fig. 7 we see that there are large bodyweight differences between the latter diet and the 'Optimal' diet. We calculated the same hazard ratios (HR=5.1) for Optimal *vs* Napier+MS and Napier+MS+2kg *vs* Napier+MS when the difference in bodyweight caused by the 'Optimal' diet with respect to the 'Napier+MS+2kg' diet is 110 kg.

Table 6: Estimated coefficients (β) and hazard ratios ($e^{\beta}$) for the effect of the covariates maize stover (MS), concentrates offered a 2 kg per day during early lactation ($early_1$) for 'Napier+MS+2kg diet'and 5 kg per day ($early_2$) for 'Optimal diet'. All coefficients $P$<0.01.

| Diets | Hazard function |
|---|---|
| | $\hat{h}(t,X)= \hat{h}_o(t)\ \exp[\beta_1 MS+\beta_2 Concentrates+\delta_1 BW]$ |
| Napier grass diet | $\hat{h}(t,X)= \hat{h}_o(t)\ \exp[0.005\ BW]$ |
| Napier+MS diet | $\hat{h}(t,X)= \hat{h}_o(t)\ \exp[-0.597\ MS +0.005\ BW]$ |
| Napier+MS+2kg diet | $\hat{h}(t,X)= \hat{h}_o(t)\ \exp[-0.597\ MS +2.232\ early_1 +0.005\ BW]$ |
| Optimal diet | $\hat{h}(t,X)= \hat{h}_o(t)\ \exp[-0.597\ MS +1.727\ early_2 +0.005\ BW]$ |

### 3.3 Lifetime productivity and random mortality (Scenario 3)

Mortality of animals at all stages reduced productive life significantly independently of the type of diet (Fig. 7B). With the mortality used in the simulations (reported by Bebe et al. (2003b) for the highlands of Kenya), only between 28 and 31% of the cows survived 13 years. Average lifetime ranged between 7.3 and 8.1y for different diets, and between 68 to 72% of the cows that survived, calved at least once (Table 7). Productivity indicators (number of calves, milk and days in milk) calculated for the cows that calved, were reduced about 43−65% depending on the diet (Table 7). This was the result of having fewer calves because productive life was significantly shortened.

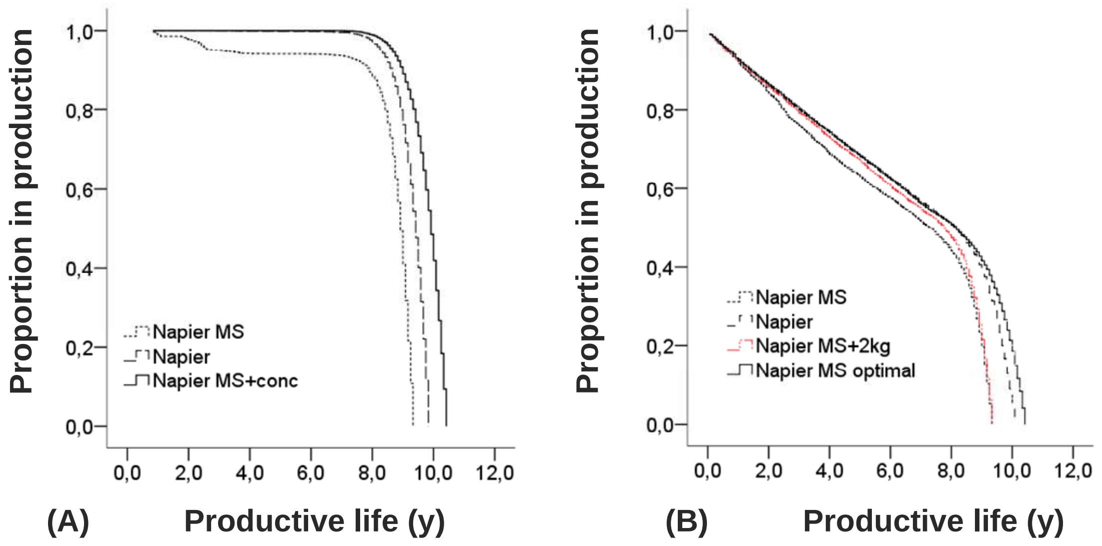


Figure 7: Kaplan-Meier survival curves for: (A) Productive life span of cows fed 3 different diets, sole Napier grass (Napier), Napier grass supplemented with maize stover (Napier MS), and Napier grass supplemented with 0.5 kg concentrates per day except during early lactation (5 kg) and late lactation (1 kg) (Napier MS optimal), and mortality rate set to nil, and (B) Productive life of cows fed 4 diets, the same as in (A) plus Napier grass supplemented with maize stover and 2 kg of concentrates during the whole lactation (Napier MS+2kg) and with the actual measured mortality rate of the dairy system under study.

In the simulations, the effect of removing animals from the population of simulated cows is observed on the indicators of lifetime productivity due to the shortened productive life. There were no significant differences in average days open per calving interval between no mortality or random mortality. Milk production could be increased on average by 1,400 kg per lactation by supplementing the diet with 5kg concentrates during early lactation and 1 kg during late lactation. But for poor farmers who do not have a large investment capacity, reducing mortality helps to secure the asset and increasing productivity. The ‘Napier+MS’ diet with the baseline mortality results in 3,700 *vs* 10,700 kg of milk per lifetime that may be obtained if mortality was nil (Table 7). Supplementing the cows with 2 kg of concentrate under the mortality baseline increased the lifetime productivity to 8,200 kg of milk, half of what could be achieved (17,000 kg of milk) if there was no mortality. Mortality reduced the productive life (days in milk) and therefore returns to investment. This can also be seen in the amount of milk produced per day, the milk produced per day of lifetime, and the days in milk per day of lifetime (Table 8).

We calculated that milk represented about 90% of the total gross income from an individual cow. In these simulations diet had a larger effect on economic indicators than increased mortality. The cost of a day open increased as the quality of the diet

Table 7: Effect of diet and mortality on indicators of lifetime productivity. The diets consisted of Napier grass (Napier), Napier grass supplemented with maize stover (MS) 6 months per year (Napier+MS), Napier grass, maize stover plus 2 kg concentrates during the whole lactation (Napier+MS+2kg), and Napier grass, maize stover supplemented with 0.5 kg concentrates except during early lactation (5 kg) and late lactation (1 kg), named the Optimal diet.

| Diet | Mortality rate | Survived (%) | Survival time (y) | Calved (%) | Productive life (y) | Calves (# lifetime$^{-1}$) | Cumulative milk (kg lifetime$^{-1}$) | Days in milk (d lifetime$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| Napier | nil | 100 | 13.0 | 100 | 9.4 | 6 (5.7)[1] (2−9) | 13700 (2300−18400) | 1673 (548−2707) |
| | actual | 31 | 7.8 | 70 | 4.4 | 3 (3.0) (0−9) | 7500 (0−18400) | 913 (0−2677) |
| Napier+ MS | nil | 94 | 13.0 | 100 | 8.9 | 6 (5.2) (2−9) | 10700 (900−15000) | 1521 (274−2616) |
| | actual | 28 | 7.3 | 70 | 4.0 | 2 (2.8) (0−8) | 3700 (0−15300) | 608 (0−2433) |
| Napier+MS +2kg | nil | 100 | 13.0 | 100 | 9.0 | 6 (5.6) (3−10) | 17000 (6500−23000) | 1643 (603−2585) |
| | actual | 31 | 8.1 | 68 | 4.0 | 3 (2.9) (0−8) | 8200 (0−27700) | 821 (0−2403) |
| Optimal diet | nil | 100 | 13.0 | 100 | 9.9 | 7 (7.3) (3−11) | 25400 (11400−35400) | 2129 (882−2981) |
| | actual | 30 | 7.9 | 72 | 5.0 | 4 (3.9) (0−10) | 14400 (0−35500) | 1156 (0−3011) |

[1] Medians and ranges between parentheses are shown. Means are indicated for number of calves, next to the medians

Table 8: Effect of diet and mortality on lifetime efficiency ratios. The diet consisted of Napier grass (Napier), Napier grass supplemented with maize stover (MS) 6 months per year (Napier+MS), Napier grass, maize stover plus 2 kg concentrates during the whole lactation (Napier+MS+2kg), and Napier grass, maize stover supplemented with 0.5 kg concentrates per day except during early lactation (5 kg) and late lactation (1 kg), named the Optimal diet.

| Diet | Mortality rate | Milk per day in milk (kg d$^{-1}$) | Milk per days open (kg d open$^{-1}$) | Milk per lifetime (kg d lifetime$^{-1}$) | Days in milk per lifetime (d d lifetime$^{-1}$) |
|---|---|---|---|---|---|
| Napier | nil | 8.5 | 6.7 | 2.9 | 0.35 |
| | actual | 8.3 | 6.3 | 2.4 | 0.28 |
| Napier+MS | nil | 7.2 | 5.3 | 2.3 | 0.32 |
| | actual | 5.3 | 4.4 | 1.3 | 0.25 |
| Napier+ MS+2kg | nil | 10.6 | 8.9 | 3.6 | 0.35 |
| | actual | 9.9 | 7.9 | 2.7 | 0.26 |
| Optimal diet | nil | 12.0 | 14.6 | 5.4 | 0.45 |
| | actual | 11.9 | 13.2 | 4.5 | 0.37 |

improved. Income per day in production was also greatly affected by the diet and decreased when mortality increased because of its effects on reducing number of lactations. Income per day of lifetime was both affected by diet and mortality because of the effect of diet on milk production and the effect of mortality on shortening productive life. The baseline mortality of 15% for young calves, of 7% for cows in production (2−6 y), and 12% for older cows, accounted for about 40−65% of income reduction (Table 9).

Table 9: Effect of factors (diet and mortality) affecting indicators of lifetime productivity and economic indicators. The analysis did not include the value of the disposed cows, and therefore represent the worst case scenario. The diet consisted of Napier grass (Napier), Napier grass supplemented with maize stover (MS) 6 months per year (Napier+MS), Napier grass, maize stover plus 2 kg concentrates during the whole lactation (Napier+MS+2kg), and Napier grass, maize stover supplemented with 0.5 kg concentrates per day except during early lactation (5 kg) and late lactation (1 kg), named the Optimal diet.

| Diet | Mortality rate | Cumulative income[1] (KSh lifetime$^{-1}$) | Income from milk (KSh lifetime$^{-1}$) | Income from calves (KSh lifetime$^{-1}$) | Income per day open (KSh d open$^{-1}$) | Income per day in milk (KSh d$^{-1}$) | Income per lifetime (KSh d lifetime$^{-1}$) |
|---|---|---|---|---|---|---|---|
| Napier | nil | 298,100 | 274,100 | 24,000 | 142 | 178 | 68 |
| | actual | 161,220 | 149,220 | 12,000 | 161 | 177 | 37 |
| Napier+MS | nil | 238,760 | 214,760 | 24,000 | 121 | 157 | 55 |
| | actual | 81,080 | 73,080 | 8,000 | 116 | 133 | 19 |
| Napier+ MS+2kg | nil | 363,120 | 339,120 | 24,000 | 187 | 221 | 83 |
| | actual | 175,280 | 163,280 | 12,000 | 206 | 213 | 40 |
| Optimal diet | nil | 536,780 | 508,780 | 28,000 | 299 | 252 | 123 |
| | actual | 304,240 | 288,240 | 16,000 | 371 | 263 | 69 |

[1] 1US$= 67 KSh, Milk price: KSh 20, female calves: KSh 6000, male calves: KSh 2000.

# 4. Discussion

## 4.1 Designing diets to maximise lifetime productivity

The allocation of different amounts of concentrates throughout the lactation showed the advantages in terms of lifetime productivity of the diet that more closely followed the peak energy requirements of the cows. Supplementing grass hay with 8 kg of concentrates per day during the first 75 days of lactation produced significantly more milk than supplementing with 4 kg during 150 days or 2 kg during the whole lactation (Kaitho et al., 2001), this supplementation could be withdrawn after early lactation without lowering milk production. Our simulations identified a different best fit strategy than that of Kaitho et al. (2001), and this is due to the different temporal scales used for the analyses (individual lactations *vs* lifetime), and probably also due to the large inherent variability between cows in feeding experiments (Strickland and Broster, 1981). In our study, the diet of Napier grass supplemented with 8 kg of concentrates allowed nutritional requirements at peak production to be met and therefore it could result in larger milk production per lactation. In the long term the energy deficit in the rest of the lactation resulted in less cumulative milk production, bodyweight loss, and poor body condition which had a negative impact on reproduction. Farmers' objectives of keeping cattle in the Central Highlands of Kenya are producing milk for the market – a regular source of cash – and for family consumption, with minimal associated risk to the investments in inputs for cattle (Bebe, 2003). Cattle are also considered an asset that can be converted into cash in case of need (cash buffer), a capital reserve (Moll et al., 2007). This implies that disposal decisions are rarely based on productive reasons and that farmers keep cattle as long as they provide cash income, play an insurance and finance role, or provide manure for enhancing productivity of soils. This emphasises the need to look for opportunities for small step improvements in lifetime productivity rather than short-term large productive increments per lactation. The diet that would allow to achieve potential production, must contain more energy than the 'Napier+4kg' diet to reduce protein surpluses during the dry periods. This could be achieved by increasing the proportion of maize stover, or using Napier grass of slightly lower protein contents. Introducing small changes increases the likelihood of adoption because this is more in line with the potential for investing in technologies by smallholders.

Our results agree with empirical studies that indicate that improving feed quality leads to higher milk yield, increases productive life by reducing age at first calving and days open of cross bred cows fed tropical forages (Vargas et al., 2001). However, the use of concentrates in smallholders' dairy systems is restricted due to limited cash flows. Targeting supplementation to early lactation has a major effect on the performance during the entire lactation. Our study shows that supplementing 8 kg of concentrates only during early lactation may improve the milk yield of the first two lactations but, in the long run, the cow's body condition deteriorates due to severe weight losses and as a result reproductive performance is hampered. Small amounts of concentrates supplemented during early stages of the calf development followed by 5 kg during early lactation allowed three-fold increases in milk during the lifetime of the cow, because of the stabilising effect on body condition.

Smallholders usually purchase less fodder when crop residues are available (Romney et al., 2004). Adding maize stover to the Napier grass diet delays age at first calving and prolongs calving intervals as shown by the survival analysis, with relatively large economic consequences. Keeping animals in good body condition is needed to ensure reproduction. Poor diets were responsible for long calving intervals, and shortened productive life. Supplementation with concentrates partly compensates for the negative effect of adding maize stover and the level of compensation clearly depended on the magnitude of the bodyweight gain during the calving interval. The 'risk minimising feeding strategy' using only Napier grass and crop residues actually increased calving intervals. A major challenge for research is how to match the production potential of the cows with available resources in a realistic manner. Grass intake is depressed (cf. Fig. 5) when concentrates are supplemented although the total intake is increased. This means that per lactation the feed costs are slightly higher for the supplemented diets. Of course, incomes derived from feeding pure grass diets are reduced because of the longer non-productive periods when cows consume only Napier grass. The cost of concentrates accounts for about 15−20% of the gross income, while supplementing Napier grass with concentrates results in a two-fold increase in gross income. Most dairy farmers in Central Kenya allocate around 9−22% of their land to grow Napier grass, amounting to about 0.15 ha $TLU^{-1}$ on average (Bebe, 2003). With an average yield of 16 t ha $y^{-1}$ (Muia, 2000), this may supply only between 12−18% of the Napier consumption requirements per year for one cow, so the feed deficit has to be purchased from the market. Because milk accounts for about 90% of the total gross income from dairy, selling calves to contribute to buy feedstuffs appears to be a sensible strategy to increase lifetime productivity.

## 4.2 Lifetime productivity and mortality

Endemic and production diseases are more important in intensive systems and can be addressed through farm-scale interventions. Feeding concentrates was found to be an indicator of higher income in dairy farms of the Kenyan highlands (Van Schaik et al., 1996), although farmers often associated increased concentrate use and improved animal health care with income instability. The adoption of improved technologies requires greater market stability so that the associated risks are reduced (Romney et al., 2003). Focusing on improving diets may have an impact on lifetime productivity if survival and productive life are not excessively reduced by poor health care. Perry et al. (2002) proposed a framework to identify livestock research opportunities to contribute to poverty alleviation by securing assets, reducing the constraints to intensification or improving market opportunities. These authors recognised the difficulties of assessing the benefits of specific interventions from products of the research on the expected benefit to the poor. Our study and the tool we developed are a contribution to assist in assessing the likely effects of component technologies on the productivity of the dairy system. We estimated the production gap due to baseline mortality and what could be gained through improving feeding strategies. Poor farmers feeding poor diets (e.g. Napier grass mixed seasonally with maize stover) have much more to gain in terms of higher and more secure income from improving animal health than from a large investment in feeds. Constraints to this are of course the delivery and adoption of health services, issues more related to institutional development.

Our results suggest that it is feasible and economically viable to increase lifetime productivity of dairy cows in smallholder systems but the focus should not only be on promoting improved diets but also on reducing mortality, especially when costs justify doing so. Supplementing Napier grass with enough amounts of concentrates that match nutritive requirements helps to reduce risk in cattle production. Technologies are not widely adopted, however, because market instability affects farmers' perception of the risk of milk production. Calf (and heifer) mortality combined with long calving intervals associated with poor breeding decisions limit replacement of heifers available in smallholders mixed systems (McDermott et al. 1999). Our study shows the impacts on milk production and reduced income due to involuntary culling before the expected survival time. Ngategize (1989) reported similar high mortality for calves (15% for females) in Northern Tanzania. In his study, the benefits of increasing animal survival by 5% (higher milk production, higher offtake and higher capital value) exceeded the costs of implementing a disease control programme. Diarrhoea, followed by pneumonia were the most common causes of sickness and mortality in an extensive on-farm study carried out in Kiambu, central Kenya (Gitau et al., 1994) where mortality of calves was as high as 22%. Tick control has reduced significantly the incidence of East Coast fever in the intensive dairy systems of the Kenyan highlands. The use of bedding and a low frequency of cleaning of the cattle shed have shown to be related to higher mortality (Gitau et al., 1994). Van Schaik et al. (1996) observed that milk production and calving intervals were the main indicators describing the performance of dairy farms in Central Kenya, and that the costs of health services on farm performance were not significant.

### 4.3 The strengths and weaknesses of modelling complex livestock systems

The model captures the effect of better quality diets on productivity indicators in a realistic way. We compared the model output on lifetime indicators with result of surveys done for animals of a herd of the same breed. For instance, Goshu (2005) studied productive and reproductive performance of a large herd (*n* = 600) of crossbred Boran-Friesian Holstein cows in the highlands of Ethiopia and observed that on average 4 calves were born in an average herd life of 8 (3−17) years during which 12,000 kg (981−44,500) of milk were produced. The F1 progeny of the cross had a longer lifetime (8.5 y), more calves (6) and more milk (14,000 kg). Tadesse and Dessie (2003) observed calving intervals of 436−498 days for Holstein-Friesian cows and their crosses in the highlands of Ethiopia. This corresponded to milk yields per lactation of between 2,000 and 3,000 kg.

We did not include the effect of chronic diseases in reducing milk production or affecting reproduction, which is a limitation of our study. We used the average calving and mortality rates reported for the region and system under study. This includes the effect of diseases on reproduction but not the effects on production. Bebe et al. (2003b) observed in the highlands of Central Kenya that diseases and cash needs were the main causes for involuntary culling. Poor performance only caused between 5−10% of the disposal. Most cows that were disposed were either pregnant or lactating which contrasts markedly with the strategy of dairy farmers in Northern Europe where pregnancy reduced the likelihood that a farmer will dispose of a cow (Gröhn et al., 2003). This highlights the importance of the setting in which farmers operate, and challenges system analysts to design models (or decision support systems) that properly represent the ‘least risky’ decision making of smallholder farmers.

Gröhn et al. (2003) modelled the effect of diseases on production and described the incidence of diseases probabilistically according to stage of lactation and observed occurrence. Diseases leave less room for voluntary culling (room for manoeuvre, although they reduce the asset value of the animal), and of course they reduce returns to investments. Validation of our modelling approach is difficult because models cannot easily account for adaptive management, which is very important in resource limited systems. For example, the feeding strategies were simplified to capture large differences over the long-term, but farmers would adjust feeding of animals in lactation in an opportunistic fashion, depending on cash availability and labour constraints. Thus the overall quality of the diet changes in time because it follows management decisions related to the reproductive status of the animal. The quality of the diet also varies between seasons and between years, which of course impacts on animal production. However, the approach we followed was useful to explore the magnitude of the effect of changes in feeding management that may result in benefits in the long term. Adding variability to the forage production and to the supply and demand for inputs (concentrates), factors (labour, cows) and products (milk, forage) would allow to analyse risk of the dairy systems of the highlands of Kenya.

## 5. Conclusions

Lifetime productivity of dairy systems can be improved by increasing feed intake through targeting productive animals and adding good quality supplements to the poor basal diets. These are feasible strategies that need to fit the broader livelihood objectives of smallholder farmers. The modelling approach used here was suitable to explore the effect of feeding in the smallholder dairy system and to encompass the temporal scale. Survival analysis proved to be a useful tool to disentangle the relative effect of the diets components in prolonging age at first calving and calving intervals. Supplementing diets with concentrates targeting physiological stages of high nutritive requirements allows large increments in indicators of lifetime productivity. If optimised diets are used with actual mortality due to poor health care, farmers are prevented from earning higher and more stable incomes. Improving lifetime productivity will require both investments in diet quality and health care programmes.

Chapter 5

# Analysing integration and diversity in agro-ecosystems by using indicators of network analysis[†]

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## Abstract

Diverse and integrated agro-ecosystems are usually referred to as sustainable systems. Diversity of farming activities may increase the stability of the production of a farm and reduce risks for resource-poor households, while integration of activities using the outputs of one activity as input in another activity may reduce dependency on external resources. In practice, diversity and integration are poorly defined and there is no method to assess diversity and integration in agro-ecosystems, which hampers the exploration of their potential benefits. We introduce a method based on Network Analysis to characterise and assess the diversity and integration in farm household systems. We used the Finn Cycling index (FCI) to characterise the degree of integration of farming activities, which are the compartments of the system. Diversity can be characterised by using measures of communication theory − the Average Mutual Information (AMI) and its upper boundary the statistical uncertainty (HR). The indicators are discussed in an application to mixed crop-livestock systems of the highlands of Northern Ethiopia where we used nitrogen (N) flows to illustrate the utility of the method. We conclude that the indicators are useful to support discussions on diversified and sustainable agro-ecosystems and allow assessment of the effects of different farm management to improve system design. The definition of the agro-ecosystem and its compartments (farming activities) and scales strongly affect the outcomes of the evaluations. The potential of NA for drawing recommendations on sustainable management depends on proper systems definitions and the objectives of study.

**Keywords:** Ecological network analysis; farming systems analysis; Africa; nitrogen flows; systems design

# 1. Introduction

Farm household systems are a specific type of agro-ecosystems in which the rural household is a central compartment of the system. It is hypothesised that diverse and integrated farm household systems are sustainable agro-ecosystems (Dalsgaard and Oficial, 1997) because diversity and integration may enable the realisation of complementarities between different activities and increase resource use efficiencies. Diversity in farming activities may increase, for example, income stability and reduce income risks of resource-poor households (Ellis, 2000; Niehof, 2004). Integrated farm household systems use the outputs of one activity as input in another activity, which may reduce adverse effects to the environment and decrease the dependency on external resources through recycling (Edwards et al., 1993; Vereijken, 2002). Cycling of energy and nutrients is considered one of the most important features that confers stability to ecosystem functioning (Allesina and Ulanowicz, 2004). In practice, diversity and integration are still poorly defined and although there have been several studies that focused on integrated agro-ecosystems (Prein, 2002; Pant et al., 2005), there is no practical method to characterise, quantify, and assess integration of diverse agro-ecosystems. This hinders the discussion on the performance of diverse and integrated agro-ecosystems and the design of more resource efficient, and economically viable systems. We define *integration* in agro-ecosystems as the degree to which the compartments (or activities in such systems) are interconnected by flows of material. In agro-ecosystems that are *diverse,* the number of choices for flows of material is larger than in relatively simple, often specialised or non-diverse agro-ecosystems. We introduce and apply network analysis (NA) to quantify the degree of integration and diversity of farm household systems using a set of indicators. NA is an input-output analysis originally developed in economics (Leontief, 1951) that was introduced into ecology by Hannon (1973) to quantify relationships within ecosystems (Fath and Patten, 1999). Leontief developed input-output analysis to estimate the amount of raw materials to produce a certain quantity of goods. This analysis can be applied in fields of science in which systems can be conceptualized as networks of interacting compartments exchanging materials. In farm household systems it can be used to analyse input-output relationships among different compartments or household activities. The flow analysis of Finn (1980), belongs to the early developments of NA where it was used to study throughflow of nutrients or energy, and cycling in ecosystems. The Shannon index, derived from communication theory (Shannon, 1948), was introduced in ecology by MacArthur (1955) to evaluate flow patterns in ecosystems. Later, Rutledge et al. (1976) introduced another measure of communication theory, i.e. the average mutual information (AMI) to study the organisation of nutrients and energy flows in ecosystems. AMI has been proposed by Ulanowicz (1980; 1997; 2001) to measure system organisation and how the structure of the flows in a ecosystem is refined to increase autocatalysis (Odum, 1969). Since the earlier developments of NA, the method has been applied to study ecosystem properties (e.g. Baird and Ulanowicz, 1993; Christian et al., 1996; Heymans et al., 2002) but seldom to agro-ecosystems (e.g. Fores and Christian, 1993; 1997; Groot et al., 2003). The objective of this study was to assess the potentials and limitations of NA to evaluate integration of diverse agro-ecosystems, specifically indicators of flow analysis (throughflow, throughput and cycling) and indicators from communication theory (AMI and the statistical uncertainty − that measure diversity of the network connections) are addressed. The method is illustrated for mixed farm household systems from the Ethiopian highlands. First, we introduce the method, the system conceptualisation and the indicators using theoretical examples to illustrate their meaning. Secondly, we present a case study from the highlands of Northern Ethiopia where the method is applied, and the consequences of different management options for the degree of integration and diversity are explored. Finally, a partial sensitivity of the method is performed. We end the article with conclusions on the appropriateness of the indicators to characterise diversity and integration of agro-ecosystems.

# 2. Materials and methods

## 2.1 Network analysis of nutrient flows

NA is formalised by using matrices based on the material flows of the studied network and a number of indicators. The material flows characterise the internal organisation of the system. In this study, we use flows of nitrogen (N) to quantify the organisation of the system because this resource is often the most limiting production factor in tropical low-input agriculture and it can be managed by farm households. The selection of the system boundary depends partly on the purpose of the study. In our case it is defined by the resource base of the farm household, which consists of a number of compartments (activities) that may interact. We use one year as the temporal unit of analysis, because this is a common time horizon for agricultural production.

### *2.1.1 Conceptualising the system*

After having defined the boundary of the network, the next steps in NA are to define the $n$ compartments, and to quantify their interactions (N flows). For farm households, compartments are defined as farming activities that contribute directly (e.g. provide food) or indirectly (e.g. through cash income) to the consumption of the farm household and have an impact on the N resource use (Langeveld et al., 2008). Farming activities can be characterised in terms of N inputs and N outputs of which the latter can be used in other farming activities or can be exported from the system.

*2.1.2 Indicators from Network Analysis to assess integration*

In this section the indicators used to assess size, activity and cycling in ecosystems (Finn, 1980) are explained using a theoretical example. The simplest network is a system with two compartments ($H_1$ and $H_2$), for which storage ($x_1$, $x_2$) and flows are quantified ($y_{01}$, $z_{01}$, $f_{12}$, $f_{21}$, $y_{02}$, $z_{20}$) (Fig. 1). This system is defined by the following elements: $H_i$ is the compartment i, $\dot{x}_i$ is the change in the storage of compartment $H_i$, $y_{oi}$ is the outflow from compartment $H_i$ to the external environment, $z_{io}$ is the inflow from the external environment to compartment $H_i$, and $f_{ij}$ is an internal flow from compartment $H_j$ to compartment $H_i$. The flows are expressed in a common unit, i.e. kg N $y^{-1}$, in which case storage and compartmental size are expressed in kg or tonnes of N. Nitrogen flows move from one compartment (j=0…n) to another (i=1…n, n+1, n+2), where n+1 accounts for usable exports (e.g. grain, milk) and n+2 accounts for dissipations (e.g. animal excreta in pastures, human excreta in latrines). Here compartment j=0 is used to keep track of the imports. We use the convention of usable (n+1) and unusable export or dissipations (n+2) from Hirata and Ulanowicz (1984). Storage in a compartment is an estimation of the amount of N contained in the total human and animal mass (expressed as kg N per compartment) while for cropping activities or field compartments storage is an estimation of the amount of N contained in the top soil layer (0.30 m), also expressed in kg N per compartment.

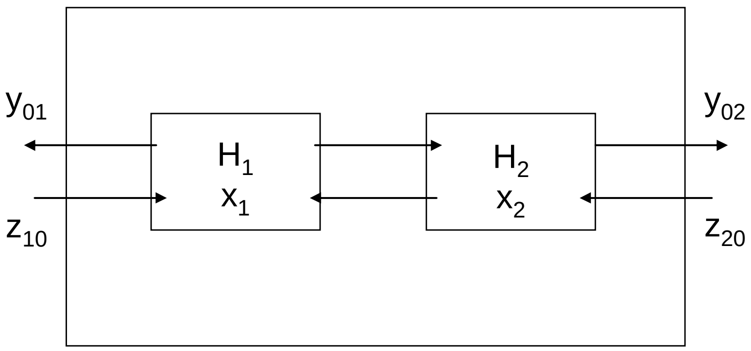



Figure 1: System representing a network with two compartments $H_1$ and $H_2$, and their respective storages $x_1$ and $x_2$, the internal flows $f_{12}$ and f $_{21}$, and exchanges from $z_{10}$ and $z_{20}$ and to the external environment, i.e. $y_{01}$ and $y_{02}$. The rectangular box defines the system boundaries. Source: Finn (1980).

Based on this conceptualisation of the network, Finn (1980) developed a number of indicators that characterise N flows in the system:

Imports (IN) is the amount of N that is imported from the external environment into the system (Eq. 1).

$$IN = \sum_{i=1}^{n} z_{io} \qquad \text{(Eq. 1)}$$

Total inflow (TIN) into the system is the sum of N flows from external inputs (z) into all n compartments plus the amount of N contributed to the system total flows by the storage of all compartments $(\dot{x}_i)$, i.e. negative changes in the storage (Eq. 2).

$$TIN = \sum_{i=1}^{n} z_{io} - \sum_{i=1}^{n} (\dot{x}_i)_- \qquad \text{(Eq. 2)}$$

These definitions take the input perspective (Finn 1980), and are used to assess whether a network accumulates or loses material.

Throughflow ($T_i$) is the total flow from other compartments to compartment i ($f_{ij}$) plus the inflow from the exterior (z) and the N flows contributed by the storage of compartment $H_i$ (the negative changes in storage $x_i$) (Eq. 3). This definition takes the input perspective.

$$T_i = \sum_{j=1}^{n} f_{ij} + z_{io} - (\dot{x}_i)_- \qquad \text{(Eq. 3)}$$

Total System Throughflow (TST) is the sum of all the throughflows ($T_i$) in the system (Eq. 4). It represents the N pool within the system that contributes to the production or activity. The ratio IN/TST is an indicator of dependency of the system on external inputs.

$$TST = \sum_{i=1}^{n} T_i \qquad \text{(Eq. 4)}$$

Path length (PL) is the average number of compartments that a unit of inflow passes through (Eq. 5). It is a measure of the cycling intensity within the system. Part of the nutrients entering the system may flow through one or more compartments and leave the system, while another part may be recycled repeatedly before leaving the system.

$$PL = \frac{TST}{TIN} \qquad \text{(Eq. 5)}$$

Throughput (T..) is the sum of all flows in the system (Eq. 6).

$$T.. = \sum_{i,j=1}^{n} T_{ij} \qquad \text{(Eq. 6)}$$

Each flow $f_{ij}$ can be expressed as a fraction $q_{ij}^{**}$ of the total flow ($T_j$) leaving the compartment $H_j$, then throughflow can be expressed as:

$$T_i = \sum_{j=1}^{n} q_{ij}^{**} T_j + z_{io} - (\dot{x}_i)_{-} \qquad \text{(Eq. 7)}$$

Expressed in matrix form:

$$T = Q^{**}T + z - (\dot{x}_i)_{-} \qquad \text{(Eq. 8)}$$

where Q** is a matrix with the $q_{ij}^{**}$ elements, T is a column vector of throughflows, z is a column vector of inflows and $(x_i)_{-}$ is a vector of negative state derivatives. Solving for T gives:

$$T = \left[I - Q^{**}\right]^{-1}\left[z - (\dot{x}_i)_{-}\right] \qquad \text{(Eq. 9)}$$

Where I is the identity matrix, the matrix $[I - Q^{**}]^{-1}$ is called N**, whose i,j element indicate the flow in $H_i$ due to an unit of flow starting in $H_j$. Cycling efficiency ($RE_i$) (Eq. 10) is the fraction of throughflow ($T_i$) that returns to the compartment $H_i$, and it can be found by examining the diagonal of matrix N**. The element $n^{**}_{ii}$ represents the flows generated by a unit of flow that started in $H_i$.

$$RE_i = \frac{n_{ii}^{**} - 1}{n_{ii}^{**}} \qquad \text{(Eq. 10)}$$

The Finn's cycling index (FCI) is the proportion of TST that is recycled (Eq. 12) within the system. FCI is calculated by dividing the relative cycling efficiency of all compartments ($TST_c$) (Eq. 10) by the total TST (Eq. 11). It yields values between 0 and 1, indicating either no recycling or complete recycling.

$$TST_c = \sum_{i=1}^{n} RE_i T_i \qquad \text{(Eq. 11)}$$

$$FCI = \frac{TST_c}{TST} \qquad \text{(Eq. 12)}$$

See Finn (1980) for more details on the calculation of the flow analysis indicators. We use the indicators FCI, PL and the relationship between IN/TST to assess integration in agro-ecosystems, because a more integrated system shows more internal recycling and less dependency from the external environment. Additionally, the ratio of TST/T can be used to characterise the role of the storage in the compartments to the system total flow.

### *2.1.3 Illustration of NA indicators of integration*

Here we present examples of systems, with 4 compartments, to illustrate the calculations of the indicators and to facilitate their interpretation (Fig. 2A and 2B). Systems A and B receive both inputs from the external environment (IN). For system A the total inflow (TIN) is 5, and for system B it is 4. Comparing IN and TIN allows to assess whether a system accumulates or loses material because TIN combines the external input (IN) with the changes in compartment storage needed to support the total network flow. In these systems TIN and IN are the same because the compartment storages do not contribute to the network flows. Both systems do not accumulate or lose material; they are in a steady-state as storage $x_i$=0 and total inflows (TIN) and imports (IN) are equal.

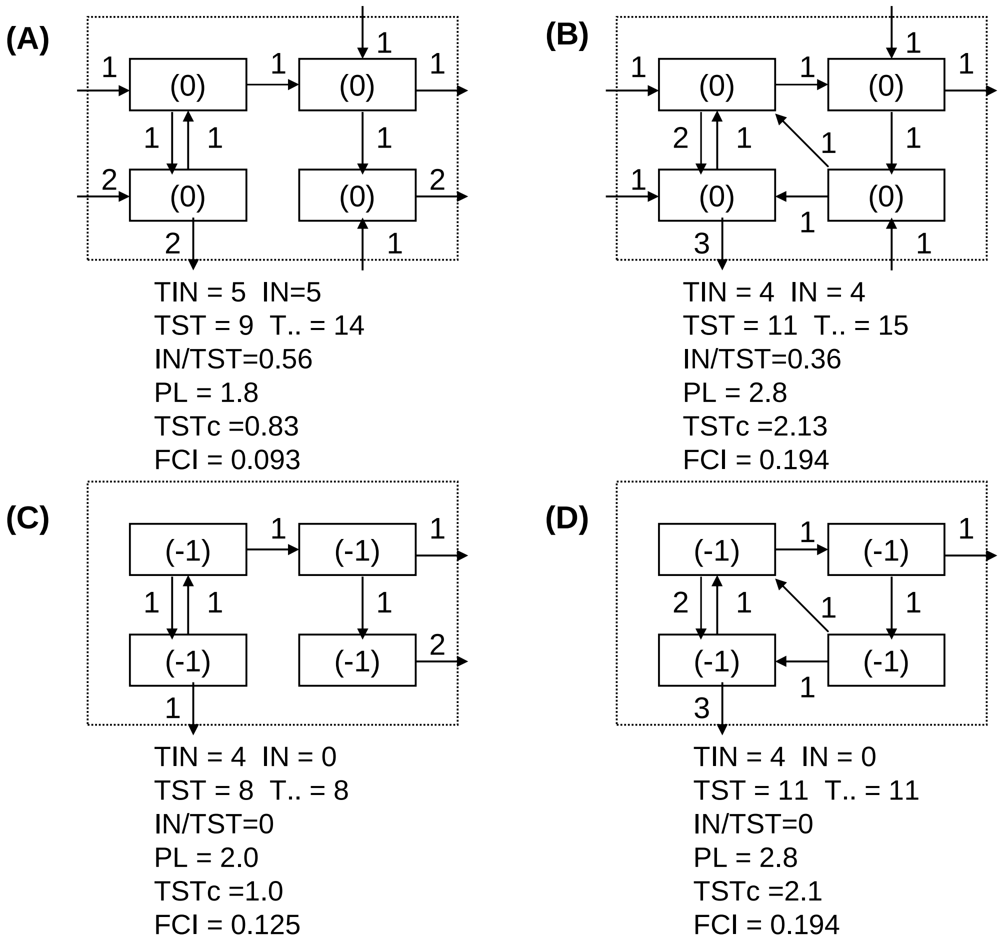



Figure 2: Examples of four systems with four compartments used to illustrate the calculations of the indicators and their interpretation. A flow is represented by an arrow and a storage is indicated between brackets. Systems A and B are in steady-state with no change in storage ($x_i$=0) and total inflows (TIN) and imports (IN) are equal. Systems C and D are not in steady state showing a negative change in storage ($x_i$<0), imports (IN)=0 and differ from total inflows (TIN), which are supported by the change in storage. See text for further explanation.

The ratio IN/TST shows that system A depends more on imports to support the system activity (TST) than system B. The total system throughflow (TST) is the sum of all material flowing through the system compartments, while the throughput (T..) sums all inputs and outputs flowing from and to all system compartments. System B differs from system A in that imports are smaller and recycling is larger. As a result, the ratio TST/T is larger for B than for system A, which means that the storage compensates for the difference between inputs and outputs.

Table 1: Flow matrix for the network shown in Fig. 2A. $H_1$ to $H_4$ are the compartments of the network with their internal transfer flows expressed in kg N per year. Compartmental throughflow ($T_i$) is calculated according to Eq. 3. Total inflows (TIN), Total Throughflow (TST), Total Throughput (T..) and Path Length (PL) are calculated according to Eq. 2, 4, 6 and 5, respectively. The elements of the Q** matrix are calculated as the fraction of the intercompartmental flow to total compartmental flow. The N** matrix is the inverse matrix $[I-Q^{**}]^{-1}$, whose elements represent throughflow values for an unit of flow that enter the column compartment.

| | $H_1$ | $H_2$ | $H_3$ | $H_4$ | Inflows (z) | $T_i$ |
|---|---|---|---|---|---|---|
| $H_1$ | 0 | 0 | 1 | 0 | 1 | 2 |
| $H_2$ | 1 | 0 | 0 | 0 | 1 | 2 |
| $H_3$ | 1 | 0 | 0 | 0 | 2 | 3 |
| $H_4$ | 0 | 1 | 0 | 0 | 1 | 2 |
| Outflows (y) | 0 | 1 | 1 | 2 | | |
| $T_i$ | 2 | 2 | 3 | 2 | | |

| | | |
|---|---|---|
| TIN | 5 | (Eq. 2) |
| TST | 9 | (Eq. 4) |
| PL | 1.8 | (Eq. 5) |
| T.. | 14 | (Eq. 6) |

Q** matrix (Eq. 8)

| | $H_1$ | $H_2$ | $H_3$ | $H_4$ |
|---|---|---|---|---|
| $H_1$ | 0 | 0 | 0.33 | 0 |
| $H_2$ | 0.5 | 0 | 0 | 0 |
| $H_3$ | 0.5 | 0 | 0 | 0 |
| $H_4$ | 0 | 0.5 | 0 | 0 |

N** matrix

| | $H_1$ | $H_2$ | $H_3$ | $H_4$ |
|---|---|---|---|---|
| $H_1$ | 1.2 | 0 | 0.4 | 0 |
| $H_2$ | 0.6 | 1 | 0.2 | 0 |
| $H_3$ | 0.6 | 0 | 1.2 | 0 |
| $H_4$ | 0.3 | 0.5 | 0.1 | 1 |

| | $H_1$ | $H_2$ | $H_3$ | $H_4$ | |
|---|---|---|---|---|---|
| $RE_i$ | 0.17 | 0 | 0.17 | 0 | (Eq. 10) |

| | | |
|---|---|---|
| $TST_c$ | 0.83 | (Eq. 11) |
| FCI | 0.093 | (Eq. 12) |

As an example the detailed calculations of FCI (Eq. 1 to 12) for system A (Fig. 2) are presented in Table 1. Systems C and D are not in steady-state and the change in storage is negative for all the compartments. External inputs (IN) are 0 and the total inflows (TIN), which are supported by the change in storage, are in both cases 4. These systems export material to the external environment. System D recycles more material than system C, which increases the ratio TST/T because part of the activity in the network is supported by cycling and not only by the change in storage. An increase in PL is associated with an increase of cycling (Fig. 2C and 2D).

### *2.1.4 Indicators to assess diversity*

Diversity in farm household systems may be assessed straightforwardly from the number of farming activities, equivalent to species richness in ecosystems. This is however rather limited because it does not consider the fact that different compartments or activities use different types and amounts of resources (e.g. land, inputs) to produce plant or animal products that contribute differently to the household consumption.

The Shannon index (Shannon and Weaver, 1949) is the most common index used to assess (bio)diversity (Clergue et al., 2005) (Eq. 13):

$$S = -\sum_i p_i \log_2(p_i) \qquad \text{(Eq. 13)}$$

where $p_i$ is the fraction of flow $T_i$ to throughput (T..). The Shannon index (Eq. 13) sums over all $i^{th}$ linkages in the system, it quantifies the diversity of the network connections. When a flow $T_i$ is a large proportion of T.., then log ($p_i$) is close to 0, and the contribution of that compartmental flow to the system diversity is small. That will be the case of a system with few compartments, where the compartmental flow of one compartment dominates T... That system will have a low diversity in its flows network. This concept was elaborated to study how the pattern of flows is refined or organised in a network (Rutledge et al., 1976; Ulanowicz, 1980). The diversity in network connections is not necessarily used to its full extent. Mageau et al. (1998) defined the Average Mutual Information (AMI) as: "… *a measure of the information we have regarding the exchange of material within the system. If material from any compartment had the equal chance of flowing into any other compartment, then we have no information regarding the flow in the network. If all material from one compartment was transferred to only one of the potential recipients, we would have complete information regarding the flow structure*". AMI quantifies the organisation of the flows in the network (Eq. 14). In the log part of Eq. 14, the conditional probability that a flow entering i comes from j is quantified. That probability is the fraction of the flow $T_{ij}$ to all flows that enter $T_i$, divided by the product of the fraction of $T_i$ to total flows T.. and $T_j$ to total flow T... Each of these conditional probabilities are weighted by the joint probability of that flow ($T_{ij}$/T..), and these weighted ‘constraints’ are summed over all combinations of i and j in the network. For example, in a system where the total flow is divided equally among all compartments, and all compartments are connected, AMI will be 0 or very small. If few flows, which are a large proportion of T.., connect few compartments, the value of AMI will approach its upper boundary.

$$AMI = k \sum_{i=1}^{n+2} \sum_{j=0}^{n} \frac{T_{ij}}{T..} log_2 \frac{T_{ij} T..}{T_{i.} T_{.j}} \qquad \text{(Eq. 14)}$$

Statistical uncertainty ($H_R$) is the upper boundary for AMI, it is Shannon-diversity (Eq. 13) of flows given a certain value of T.. (Eq. 15). When the contribution of the flow out of a compartment ($T_{.j}$) to total system throughput T.. is small and different across compartments, diversity increases. $H_R$ increases when T is partitioned among a greater number of flows.

$$H_R = - \sum_{j=0}^{n} \frac{T_{.j}}{T..} log_2 \frac{T_{.j}}{T..} \qquad \text{(Eq. 15)}$$

AMI/$H_R$ is the proportion of diversity that is reduced by the actual pattern of flows. This may be used to evaluate the organisation of N flows to total diversity of the network connections. The units of AMI and $H_R$ are bits and the scalar k equals 1 for AMI. For more detail on AMI and its derivation we refer to Ulanowicz (2001) and Latham and Scully (2002).

*2.1.5 Illustration of diversity indicators*

In Figure 3, two groups of three systems are presented to show the meaning of AMI and $H_R$. Throughput T.. is kept constant to show differences in organisation of the flows reflected in changes in AMI, and in diversity shown in changes in $H_R$. In the first group (Fig. 3A to C), the diversity of flows changes slightly because the contribution of each of the compartmental flow ($T_{.j}$) to T.. changes little from system A to system C. However, AMI increases considerably from A to C, reflecting a selection of flow paths from almost all connections possible in system A to very few in system C. This happens when for example the most efficient path is selected for nutrient flows.

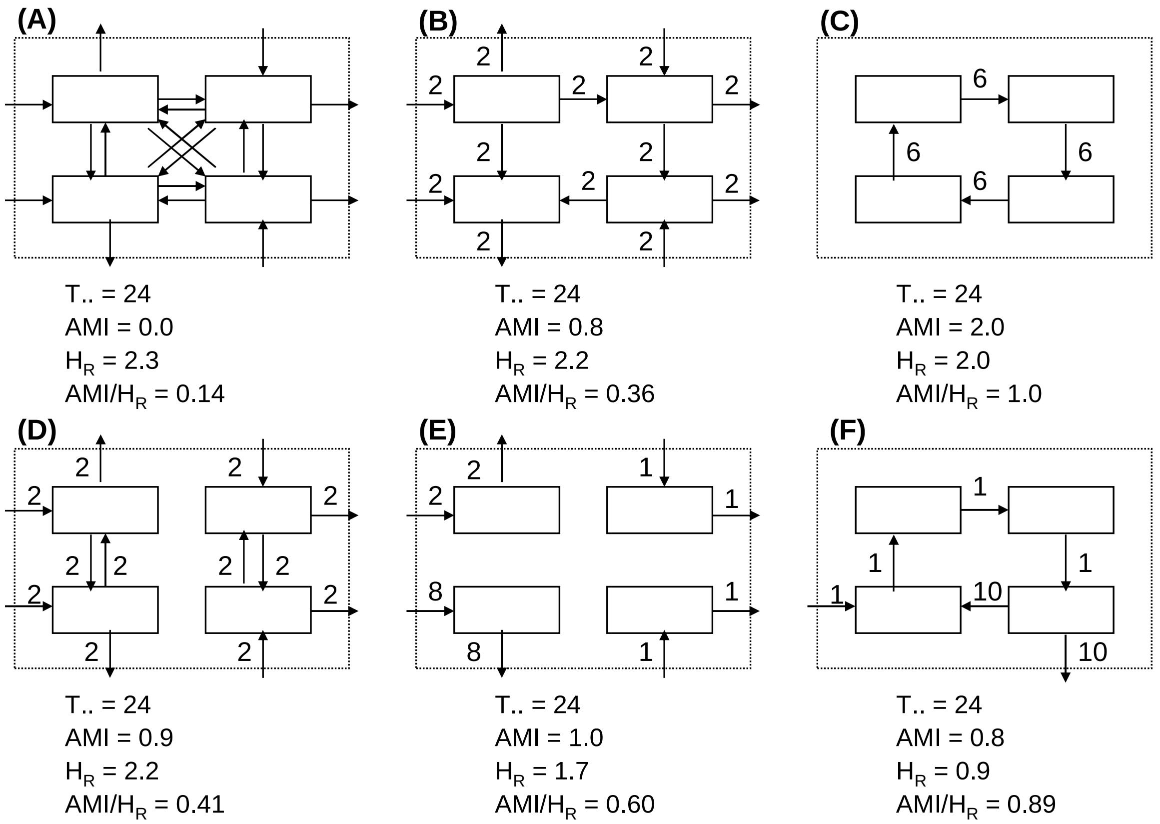



Figure 3: Examples of six systems with four compartments to show how the simplification of flow patterns increases the information content in networks. Flows are represented by arrows, and the size of the flows is indicated next to the arrow, except for system A, where all flows equal 1. From system A to C, flows become less random and therefore organisation increases. From system D to F diversity decreases, and because the flows network is simpler, AMI approaches $H_R$. See text for further explanation.

In the second group of systems (Fig. 3D to F), it is shown how the diversity of flows in the system changes due to differential contribution of each compartment to total flows. System D is less diverse than system A (each compartment contributes similar amounts to total flows), but the network of flows is more constrained, many flows of system A are eliminated in system D, and therefore the value of AMI increases. In system E, the contribution of the compartments to total flows is not uniform, diversity decreases and AMI is relatively high because of the limited number of connections between the compartments. In system F, diversity decreases further, and because the total flows are dominated by one compartment, the ratio of AMI/$H_R$ is high.

In practice, AMI and $H_R$ can be used to assess nutrient allocations between activities and resulting efficiencies. It is expected that in specialised systems, $H_R$ will be relatively low and AMI will be close to $H_R$. These adapted systems use the most efficient paths. In less specialised system, those where the nutrient allocation follows a (risk) spreading strategy, in for example marginal erratic environments where diversity is higher, AMI will be smaller. These systems are more adaptable, and may keep several (more inefficient) network connections active as a risk management strategy.

## 2.3 Application to mixed farm household systems in Ethiopia

In this section, we aim at gaining understanding on how the diversity in flow patterns relates to integration by using the indicators proposed in the previous section.

### *2.3.1 The study area*

The method was applied to farm household systems of the village Teghane (13° 45'N, 39° 41'E), Atsbi Wonberta district in Northern Ethiopia. Average farm size is about 0.5 hectare and most households grow cereals and legumes (faba beans, common beans) for subsistence. Steep slopes, stony soils, frost-risk during part of the year and seasonal rainfall constrain agricultural production. Average annual rainfall is 540 mm, of which most is concentrated in a period of only 75 days (from June to September). Livestock (dairy and beef cattle, donkeys, and sheep) graze on communal pastures and are fed crop residues and other grasses cut and carried to the farm.

### *2.3.2 Data collection*

During the 2002 growing season, a farm household survey was conducted in Teghane as part of the research programme 'Policies for Sustainable Land Management in the Ethiopian Highlands' sponsored by the Dutch Ministry of Foreign Affairs (DGIS). During a rapid diagnostic appraisal, farmers in Teghane ($n$=50) identified three household wealth classes based on land, livestock and labour (Mulder, 2003; Assefa, 2005). The poor households had no or few livestock and little land, the medium wealth households had one ox, one donkey and few sheep, and usually a labour surplus, the wealthier households had several oxen, some cattle, donkeys and sheep and they were most of the time food self-sufficient. We used three farm households, each representing a typical wealth class (Table 2).
Detailed information on household composition and consumption, farm and fields characteristics, input use to different activities, flows between activities, crop yields, animal production, sales and input and output prices were collected using the participatory NUTrient MONitoring (NUTMON) approach (De Jager et al., 1998; Van den Bosch et al., 1998). The combination of these farm household surveys, field observations and measurements and simple models provide the basis for the NA application. Intake and excretion of the livestock was estimated using a model that uses as inputs

animal type, size, grazing time and feed availability (Vlaming et al., 2001).

Table 2: Main characteristics of three types of farm household systems in Teghane, Ethiopia, i.e. poor, medium wealth and wealthy.

| *Farm household characteristics* | Poor | Medium | Wealthier |
|---|---|---|---|
| Arable land (ha) | 0.30 | 0.70 | 2.40 |
| Own land (ha) | 0.30 | 0.70 | 1.60 |
| Household members | 5 | 9 | 10 |
| Animals | | | |
| Cattle (TLUs)[1] | 1 | 4.7 | 6.3 |
| Sheep (TLUs) | 0.2 | 0.9 | 3.0 |
| Donkeys (TLUs) | - | 0.9 | 0.7 |
| Mules (TLUs) | - | 0.6 | - |
| Poultry (TLUs) | 0.01 | 0.02 | 0.04 |
| Crops | | | |
| Barley (ha) | | 0.49 | 0.55 |
| Barley irrigated (ha) | 0.23 | 0.10 | 0.38 |
| Barley rented-in (ha) | | | 0.57 |
| Wheat (ha) | | | 0.15 |
| Wheat rented-in (ha) | | | 0.68 |
| Faba beans (ha) | | 0.08 | 0.10 |
| Prickly pears (ha) | 0.07 | | |

[1] TLUs are tropical livestock units, one tropical livestock unit equals an animal of 250 kg body mass.

### *2.3.3 Data and main assumptions*

To quantify N flows we used conversion coefficients obtained from analysis of plant and soil samples taken during the survey and for those flows that were more difficult to quantify we used conversion coefficients from the literature. These coefficients and their minimum and maximum values as found in the literature are listed in Table 3. A more detailed description of the farming systems and data used can be found in Rufino et al. (2008b) and Langeveld et al. (2008).

### *2.3.4 Exploring the effect of management options*

First, we present the NA indicators for the three farm household types (baseline) followed by an exploration of the consequences of farm management changes for the indicator values. Second, a so-called improved management scenario is defined affecting NA indicators. The management changes include increased yields of barley from its current value of 2 t ha$^{-1}$ up to 3 t ha$^{-1}$, and faba-beans from their actual values of 1 t ha$^{-1}$ up to 2 t ha$^{-1}$, these yield levels were recorded in similar agro-ecosystems in the Highlands of Ethiopia (Agegnehu et al., 2006). It is assumed that the associated increase in the availability of barley and faba bean residues for feeding animals is subtracted from the feed imported from common pastures. More manure N is retained on-farm because of improved management within feasible ranges as reported by Rufino et al. (2006). We assumed that in the improved management scenario, 70% of the manure available for recycling on-farm is conserved contributing to higher application rates to crops, and resulting in the higher crop yields.

*2.3.5 Sensitivity analysis*

The objective of the (partial) sensitivity analysis was to evaluate the effect of changes in the underlying data to quantify N flows and the conceptualisation of the system on the NA indicators. We used the wealthier farm household for the sensitivity analysis. First, all parameters associated to plant and animal products and fertilisers were changed to the maximum and minimum values found in the literature (Table 3). Second, parameters related to manure management were changed to maximum and minimum values found in the literature. Third, we compared three network configurations of the same farm household system to evaluate the impact of (dis)aggregation of compartments on NA indicators, i.e. (i) the baseline configuration with 12 compartments (Fig. 4), (ii) a configuration with 4 compartments where all animal compartments were aggregated into one livestock compartment and all cropping activities into one crop compartment, and (iii) a configuration with 14 compartments where two crop compartments were split into two compartments, i.e. fields were divided into 2 plots.

# 3. Results

### 3.1 The farm households as a network of N flows

The poor, medium and wealthier farm households were each conceptualised as networks of N flows (Fig. 4). The poor farm household had 0.3 ha of land, cattle, sheep and few chickens. Livestock fed mainly on communal lands and with on-farm crop residues. No feeds were purchased to support animal production. Manure from the corral was used only as household fuel. Most milk was sold and only a small proportion was used for household consumption. Two crops were grown, i.e. (irrigated) barley (*Hordeum vulgare* L.) and prickly pear (*Opuntia* spp.). Part of the barley harvest was exchanged for labour and traction by means of share-cropping. Mineral fertilisers were applied exclusively to the irrigated barley. Food was purchased because on-farm production could not meet the household requirements. A significant amount of cash came from off-farm employment of the family head. There were no other important sources of income. The magnitude of the N flows can be seen in the N flow matrix in Table 4A.

Table 3: Conversion coefficients and management parameters to estimate N flows in the networks of the three types of farm household systems in Teghane, Northern Ethiopia. Dry Matter (DM), Fresh Weight (FW), Nitrogen (N).

| | | Coefficient values | | | |
|---|---|---|---|---|---|
| *Plant products* | Units | Actual | Minimum | Maximum | Reference |
| Barley grain DM | g kg FW$^{-1}$ | 880 | 840 | 920 | 1 |
| Barley grain N | % DM | 1.55 | 1.40 | 1.71 | |
| Barley grain energy | MJ kg DM$^{-1}$ | 14.80 | 13.32 | 16.28 | |
| Barley crop residues DM | g kg FW$^{-1}$ | 920 | 870 | 970 | |
| Barley crop residues N | % DM | 0.70 | 0.63 | 0.77 | |
| Wheat grain DM | g kg$^{-1}$FW | 870 | 830 | 910 | |
| Wheat grain N | % DM | 2.23 | 2.01 | 2.45 | |
| Wheat grain energy | MJ kg DM$^{-1}$ | 14.00 | 12.60 | 15.40 | |
| Wheat crop residues DM | g kg FW$^{-1}$ | 920 | 870 | 970 | |
| Wheat crop residues N | % DM | 0.40 | 0.36 | 0.44 | |
| Faba beans grain DM | g kg FW$^{-1}$ | 860 | 820 | 900 | |
| Faba beans grain N | % DM | 4.00 | 3.60 | 4.40 | |
| Faba beans pods energy | MJ kg FW$^{-1}$ | 3.70 | 3.33 | 4.07 | |
| Faba beans crop residues DM | g kg FW$^{-1}$ | 860 | 820 | 900 | |
| Faba beans crop residues N | % DM | 1.40 | 1.26 | 1.54 | |
| Grass DM | g kg FW$^{-1}$ | 170 | 140 | 200 | |
| Grass N | % DM | 2.40 | 2.04 | 2.76 | |
| *Organic and inorganic fertilisers* | | | | | |
| Ruminant manure DM | g kg FW$^{-1}$ | 350 | 200 | 500 | 2 |
| Ruminant manure N | % DM | 2.00 | 1.00 | 3.00 | |
| Poultry manure DM | g kg FW$^{-1}$ | 350 | 300 | 500 | |
| Poultry manure N | % DM | 3.10 | 2.64 | 3.57 | |
| Ash N | % DM | 2.00 | 1.70 | 2.30 | 1 |
| Urea N | % FW | 46.0 | 45.5 | 46.5 | |
| DAP N | % FW | 18.0 | 17.8 | 18.2 | |
| *Animal products* | | | | | |
| Sheep meat N | % FW | 2.65 | 2.52 | 2.78 | 3 |
| Sheep meat energy | MJ kg FW$^{-1}$ | 11.80 | 10.62 | 12.98 | |
| Chicken meat N | % FW | 2.90 | 2.76 | 3.05 | |
| Chicken meat energy | MJ kg FW$^{-1}$ | 9.00 | 8.10 | 9.90 | |
| Cattle meat N | % FW | 3.40 | 3.23 | 3.57 | |
| Cattle meat energy | MJ kg FW$^{-1}$ | 9.00 | 8.10 | 9.90 | |
| Cattle milk N | % FW | 0.50 | 0.48 | 0.53 | |
| Cattle milk energy | MJ kg FW$^{-1}$ | 2.90 | 2.61 | 3.19 | |
| Donkey meat N | % FW | 3.00 | 2.85 | 3.15 | |
| Mule meat N | % FW | 3.00 | 2.85 | 3.15 | |
| Eggs DM | g kg FW$^{-1}$ | 250 | 240 | 260 | |
| Eggs N | % DM | 1.85 | 1.76 | 1.94 | |
| Eggs energy | MJ kg FW$^{-1}$ | 6.80 | 6.46 | 7.14 | |
| Fraction N retention animal tissue | - | 0.20 | 0.10 | 0.30 | 1 |
| Fraction N retention human tissue | - | 0.20 | 0.10 | 0.30 | |
| Humans daily energy needs | MJ d$^{-1}$ | 9.10 | 8.19 | 10.01 | 4 |
| *Management related parameters* | | | | | |
| Fraction excreta N retention (ruminants) | - | 0.50 | 0.05 | 0.95 | 5 |
| Fraction excreta N retention (poultry) | - | 0.50 | 0.20 | 0.80 | |
| Fraction excreta N retention (humans) | - | 0.50 | 0.05 | 0.95 | |
| Fraction time spent on-farm by animals | - | 0.50 | 0.20 | 0.80 | |
| Fraction household wastage | - | 0.20 | 0.05 | 0.50 | 1 |

[1] NUTMON database, Vlaming et al. (2001); [2] De Ridder and Van Keulen (1990); [3] USDA Nutrient Data Laboratory, (USDA Nutrient Data Laboratory, 2007); [4] Bender (1997); [5] Rufino et al. (2006).

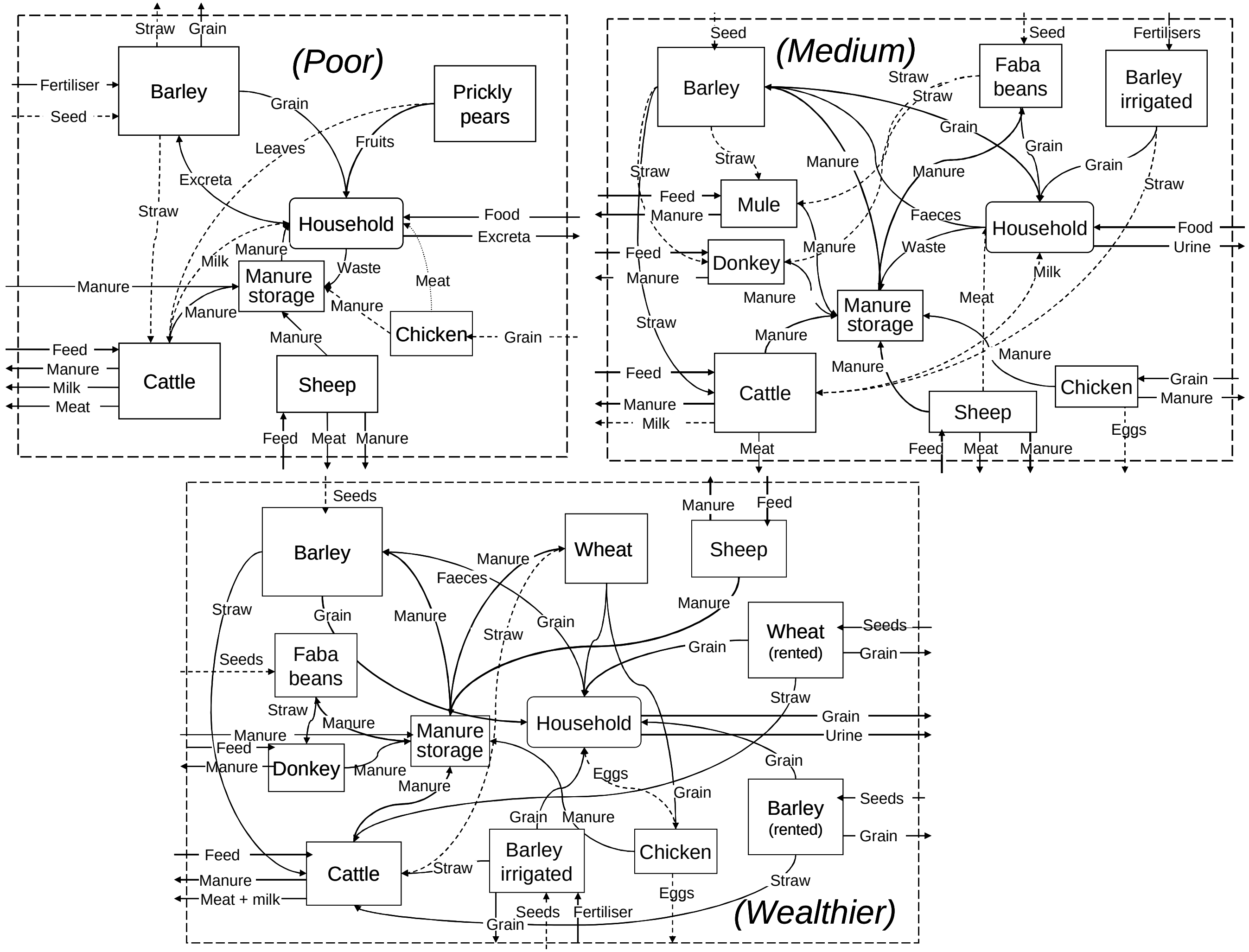



Figure 4: Flow diagrams of three different farm household types, i.e. poor with 7 compartments/ activities, medium with 10 compartments/ activities and wealthier with 12 compartments/ activities. Dotted lines are relatively small flows, thick solid lines are large N flows.

Table 4: Nitrogen flow matrix for the poor farm household in Teghane, Ethiopia consisting of 7 compartments. N flows move from one compartment (column j) to another (row i=1…n, n+1, n+2) and are expressed in kg of N per compartment per year. Inflows (column j=0) and outflows (row n+1) are the total amounts of N imported to and exported from a compartment. Storage is expressed in kg N per compartment (See Section 2.1.2 for more detail).

(A) Baseline scenario with current yields and manure management.

| i (to) | j (from) --><br>Compartment | 0<br>Inflows | 1<br>House-hold | 2<br>Prickly pears | 3<br>Barley irrigated | 4<br>Cattle | 5<br>Sheep | 6<br>Chicken | 7<br>Heap |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Household | 15.7 | 0 | 1.5 | 6.1 | 0.3 | 0 | 0.1 | 0 |
| 2 | Prickly pears | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | Barley irrigated | 7.7 | 6.6 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | Cattle | 43.4 | 0 | 1.0 | 1.1 | 0 | 0 | 0 | 0 |
| 5 | Sheep | 41.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | Chicken | 0.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | Heap | 4.2 | 6.0 | 0 | 0 | 9.1 | 8.3 | 0.2 | 0 |
| | Usable export | 0 | 0 | 0 | 5.5 | 1.2 | 0 | 0 | 0 |
| | Unusable export | 0 | 6.6 | 0 | 0 | 27.3 | 24.8 | 0.1 | 18.8 |
| | Storage | | 7.5 | 672 | 2025 | 12 | 1.8 | 0.3 | 10 |
| | (B) Scenario with increased barley yields and internal recycling through improved manure management and cattle feeding. Flows in italics changed in relation to the baseline. | | | | | | | | |
| 1 | Household | *7.8* | 0 | *3.0* | *12.6* | 0.3 | 0 | 0.1 | 0 |
| 2 | Prickly pears | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | Barley irrigated | 7.7 | 6.6 | 0 | 0 | 0 | 0 | 0 | *10.0* |
| 4 | Cattle | *34.9* | 0 | *2.0* | *8.5* | 0 | 0 | 0 | 0 |
| 5 | Sheep | 41.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | Chicken | 0.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | Heap | 4.2 | 5.9 | 0 | 0 | *11.6* | 8.3 | 0.2 | 0 |
| | Usable export | | 0 | 0 | 0 | 1.2 | 0 | 0 | 0 |
| | Unusable export | | 6.6 | 0 | 0 | *21.5* | 24.8 | 0.1 | *19.8* |
| | Storage | | 7.5 | 672 | 2025 | 12 | 1.8 | 0.3 | 10 |

The medium wealth farm household had 0.7 ha with rainfed and irrigated barley, faba beans (*Vicia faba* L.), cattle, a mule, a donkey, sheep, and chickens. Animals were fed on communal land, crop residues produced on-farm, and purchased feed. Manure was collected from the corral, composted in heaps and used as fertiliser for crops. Milk was partly sold and partly consumed by the household members, while all eggs were sold. Mineral fertilisers were exclusively applied to the irrigated barley crop. Some food was purchased, but most household consumption was met by on-farm production. Cash was generated through the sale of honey, eggs, sheep hides, and leasing out the mule. The N flow matrix is shown in Table 5A.

The wealthier farm household had 2.4 ha with common wheat (*Triticum* spp.), buckwheat (*Fagopyrum esculentum*), barley and faba beans, cattle, sheep, donkeys and chickens. The animals fed on communal land crop residues produced on-farm, and purchased supplements. Manure from the corral was partly applied to fertilise crops and partly used as fuel. Neither manure nor fertilisers were applied to the rented land.

Milk was used for home consumption. Half of the grain production of the rented land was used to pay this rent. Mineral fertilisers were applied only to the irrigated plots. Household food requirements were met by on-farm production, while the food surplus was marketed. The N flow matrix is shown in Table 6A.

Table 5: Nitrogen flow matrix for the medium wealth farm household in Teghane, Ethiopia consisting of 10 compartments. N flows move from one compartment (column j) to another (row i=1…n, n+1, n+2) and are expressed in kg of N per compartment per year. Inflows (column j=0) and outflows (row n+1) are the total amounts of N imported to and exported from a compartment. Storage is expressed in kg N per compartment (See Section 2.1.2 for more details).

| i (to) | j (from) --> Compartment | 0 In-flows | 1 House-hold | 2 Barley irrig. | 3 Faba beans | 4 Barley | 5 Mule | 6 Don-keys | 7 Cattle | 8 Sheep | 9 Chick en | 10 Heap |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (A) Baseline scenario with current yields and manure management. | | | | | | | | | | | | |
| 1 | Household | 28.2 | 0 | 2.1 | 1.7 | 16.0 | 0 | 0 | 0.5 | 0.5 | 0 | 0 |
| 2 | Barley irrig. | 2.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | Faba beans | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 21.0 |
| 4 | Barley | 0.9 | 4.8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 42.0 |
| 5 | Mule | 49.0 | 0 | 0 | 0.2 | 0.4 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | Donkeys | 41.0 | 0 | 0 | 0.2 | 0.4 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | Cattle | 165.0 | 0 | 0.6 | 0 | 3.9 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | Sheep | 100.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | Chicken | 3.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | Heap | 0 | 9.7 | 0 | 0 | 0 | 9.9 | 8.3 | 33.9 | 20.1 | 1.3 | 0 |
| | Usable export | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0.2 | 0 |
| | Unusable exp. | 0 | 27.0 | 0 | 0 | 0 | 29.7 | 25.0 | 101.8 | 60.2 | 0.3 | 25.0 |
| | Storage | | 12.1 | 904 | 349 | 2475 | 12 | 5.1 | 47.4 | 9 | 0.3 | 20.2 |
| (B) Scenario with increased barley and faba beans yields and internal recycling through improved manure management and cattle feeding. Flows in italics changed in relation to the baseline. | | | | | | | | | | | | |
| 1 | Household | *15.0* | 0 | *4.4* | *7.3* | *20.2* | 0 | 0 | 0.5 | 0.5 | 0 | 0 |
| 2 | Barley irrig. | 2.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | *10.0* |
| 3 | Faba beans | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 21.0 |
| 4 | Barley | 0.9 | 4.8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 42.0 |
| 5 | Mule | *47.3* | 0 | 0 | *0.7* | *1.6* | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | Donkeys | *39.3* | 0 | 0 | *0.7* | *1.6* | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | Cattle | *151.0* | 0 | *3.0* | 0 | *15.5* | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | Sheep | 100.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | Chicken | 3.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | Heap | 0 | 9.7 | 0 | 0 | 0 | *16.7* | *15.7* | *58.1* | *35.3* | 1.3 | 0 |
| | Usable export | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0.2 | 0 |
| | Unusable exp. | 0 | 27.0 | 0 | 0 | 0 | *22.5* | *21.2* | *62.0* | *41.0* | 0.3 | *41.0* |
| | Storage | | 12.1 | 904 | 349 | 2475 | 12 | 5.1 | 47.4 | 9 | 0.3 | 20.2 |

The N flow within each of the three farm households is dominated by the N supply to the household and the livestock (Table 4A, 5A and 6A). The largest N inflow was the result of the livestock grazing in the common pastures. The collected livestock excreta was recycled and used as fertiliser for crops and fuel for cooking. A part of the crop residues was used to feed livestock but their contribution to the total N flow in the system was relatively small.

Table 6: Nitrogen flow matrix for the wealthier farm household in Teghane, Ethiopia consisting of 12 compartments. N flows move from one compartment (column j) to another (row i=1…n, n+1, n+2) and are expressed in kg N per compartment per year. Inflows (column j=0) and outflows (row n+1) are the total amounts of N imported to and exported from a compartment. Storage is expressed in kg N per compartment (See Section 2.1.2 for more details).

(A) Baseline scenario with current yields and manure management.

| i (to) | j (from) --> Compartment | 0 Inflows | 1 Household | 2 Barley | 3 Wheat | 4 Barley irrigated | 5 Faba beans | 6 Wheat (rented) | 7 Barley (rented ) | 8 Donkeys | 9 Cattle | 10 Sheep | 11 Chicken | 12 Heap |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Household | 0 | 0 | 14.3 | 2.5 | 4.1 | 3.1 | 10.2 | 7.5 | 0 | 1.4 | 1.1 | 0.1 | 0 |
| 2 | Barley | 0.9 | 12.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 35.0 |
| 3 | Wheat | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14.0 |
| 4 | Barley irrigated | 21.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | Faba beans | 0.6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14.0 |
| 6 | Wheat (rented) | 1.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | Barley (rented ) | 0.9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | Donkeys | 32.0 | 0 | 0 | 0 | 0.3 | 0.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | Cattle | 187.0 | 0 | 9.7 | 0.4 | 2.4 | 0 | 2.0 | 2.7 | 0 | 0 | 0 | 0 | 0 |
| 10 | Sheep | 348.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | Chicken | 0 | 0 | 0 | 4.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | Heap | 18.9 | 16.9 | 0 | 0 | 0 | 0 | 0 | 0 | 6.6 | 40.2 | 69.5 | 2.5 | 0 |
| | Usable export | 0 | 0 | 0 | 0 | 6.1 | 0 | 10.2 | 7.5 | 0 | 0 | 0 | 0.1 | 0 |
| | Unusable export | 0 | 12.4 | 0 | 0 | 0 | 0 | 0 | 0 | 19.8 | 120.5 | 208.5 | 1.1 | 109.0 |
| | Storage | | 15 | 2829 | 744 | 3058 | 591 | 3102 | 2798 | 6.6 | 63 | 14.85 | 0.6 | 20 |

(B) Scenario with increased barley yields and internal recycling through improved manure management and cattle feeding. Flows in italics changed in relation to the baseline.

| i (to) | j (from) --> Compartment | 0 Inflows | 1 Household | 2 Barley | 3 Wheat | 4 Barley irrigated | 5 Faba beans | 6 Wheat (rented) | 7 Barley (rented ) | 8 Donkeys | 9 Cattle | 10 Sheep | 11 Chicken | 12 Heap |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Household | 0 | 0 | *22.5* | 2.5 | *6.8* | *13.9* | 10.2 | *11.6* | 0 | 1.4 | 1.1 | 0.0 | 0 |
| 2 | Barley | 0.9 | 19.6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 35.0 |
| 3 | Wheat | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14.0 |
| 4 | Barley irrigated | 21.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | Faba beans | 0.6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14.0 |
| 6 | Wheat (rented) | 1.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | Barley (rented ) | 0.9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | *10.0* |
| 8 | Donkeys | *26.6* | 0 | 0 | 0 | *3.2* | *3.3* | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | Cattle | *174.7* | 0 | *12.9* | 0.4 | *6.4* | 0 | 2.0 | *7.7* | 0 | 0 | 0 | 0 | 0 |
| 10 | Sheep | 348.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | Chicken | 0 | 0 | 0 | 4.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | Heap | 18.9 | 22.1 | 0 | 0 | 0 | 0 | 0 | 0 | *10.0* | *56.2* | *97.3* | 2.5 | 0 |
| | Usable export | 0 | 0 | 0 | 0 | 8.9 | 0 | 10.2 | *11.6* | 0 | 0 | 0 | 0.1 | 0 |
| | Unusable export | 0 | 19.6 | 0 | 0 | 0 | 0 | 0 | 0 | *18.5* | *104.4* | *180.7* | 1.1 | *125.1* |
| | Storage | | 15 | 2829 | 744 | 3058 | 591 | 3102 | 2798 | 6.6 | 63 | 14.85 | 0.6 | 20 |

### 3.2 NA indicators to assess integration and diversity

#### *3.2.1 Baseline scenario under current management*

All farm households depended largely on imported N (IN) to support the system throughflow (TST) (Table 7). IN represented between 66 to 70% of TST for the three farm types. IN, TIN, TST, T.. and $TST_c$ are expressed on a *per capita* basis, to allow comparison of N use of the different farm household types. The different components of IN were fertilisers, feed and food N. Fertiliser N use was limited in all three farms. The poor farm household used more fertiliser N on a per hectare basis, and imported more feed N per TLU than the other types. The medium and wealthier farm households applied manure N (109 and 30 kg $ha^{-1}$, respectively) while the poor farm household mainly used the manure as fuel. The N imported as feed represented the largest proportion (78−92%) of IN, with a daily average of 100−150 g N $TLU^{-1}$. On-farm production of food crops was insufficient to meet household needs of poor and medium wealth farm households and the energy requirements of the household members were met through importing about 3 kg N *capita*$^{-1}$ $y^{-1}$ as grain. The amount of N recycled ($TST_c$) was small for all three systems (between 1.0−2.5 kg N *capita*$^{-1}$) as compared with the total system throughflow (TST), and therefore FCIs and Path lengths (PL) were also relatively small. Average mutual information (AMI) and $H_R$ were useful to assess the organisation of flows in the network and its diversity for the three farm households: $H_R$ showed that diversity in the network connections (N flows) increased from the poor to the wealthier farm households, but differences were small. The relatively more diverse and wealthier farm households ($H_R$=2.4) did not recycle more N (FCI=2.2−2.6%) than the relatively less diverse ($H_R$=2.2) and poor farm household (FCI=2.9%), since the three farm households managed their N resources similarly. The degree of integration in the poor, medium and wealthier farm households was thus similar.

#### *3.2.2 Improved scenario under improved management*

In the alternative management scenario the integration of farming activities increases (FCI= ranged from 4.2 to 7.7%, see Table 7) because the amount of N recycled ($TST_c$) more than doubled. The dependency on external N inputs decreased (IN/TST) from 66−70% to 53−58%, while PL increased only slightly. N flows of the improved management scenario are shown in Tables 4, 5 and 6B. The diversity in the N flow pattern also increased somewhat ($H_R$= 2.4−2.6 *vs* 2.2−2.4 in the baseline) because the size of internal flows increased. AMI/$H_R$ was slightly reduced because the N flows were more homogeneously distributed.

Table 7: Network analysis of annual N flows for three farm household types in Teghane, Ethiopia, i.e. poor, medium wealth and wealthier. External inputs and indicators of the flow analysis, Total System Throughflow (TST), Throughput (T..) and cycled Total System Throughflow ($TST_c$), are expressed as kg N *per capita* (household member) per year. Fertiliser N is expressed per hectare, and feed N is expressed per tropical livestock unit (TLU). See Section 3.2 for details.

| Farm type | n | Fertiliser N | Feed N | Food N | IN | TIN | TST | T | $TST_c$ | PL | FCI | AMI | $H_R$ | $AMI/H_R$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (kg N $ha^{-1}$ $y^{-1}$) | (kg N $TLU^{-1}$ $y^{-1}$) | (kg N $capita^{-1}$ $y^{-1}$) | | | | | | – | (%) | (Bits) | (Bits) | – |
| (A) Baseline scenario with current management | | | | | | | | | | | | | | |
| Poor | 7 | 23.3 | 70.2 | 3.2 | 21.8 | 23.0 | 31.0 | 47.4 | 0.9 | 1.4 | 2.9 | 1.11 | 2.22 | 0.50 |
| Medium | 10 | 3.7 | 50.4 | 3.1 | 43.3 | 43.9 | 64.0 | 93.1 | 1.4 | 1.5 | 2.2 | 1.27 | 2.41 | 0.53 |
| Wealthier | 12 | 10.2 | 56.6 | 0 | 61.1 | 66.7 | 93.0 | 138.4 | 2.5 | 1.4 | 2.6 | 1.33 | 2.38 | 0.55 |
| (B) Scenario with increased barley yields and internal recycling through improved manure management and cattle feeding | | | | | | | | | | | | | | |
| Poor | 7 | 23.3 | 62.8 | 1.6 | 19.2 | 20.9 | 36.0 | 49.2 | 2.7 | 1.7 | 7.7 | 1.12 | 2.42 | 0.46 |
| Medium | 10 | 3.7 | 47.9 | 1.7 | 40.0 | 40.0 | 70.0 | 94.0 | 3.5 | 1.8 | 5.0 | 1.31 | 2.59 | 0.51 |
| Wealthier | 12 | 10.2 | 54.9 | 0 | 59.3 | 64.2 | 103.0 | 146.4 | 4.4 | 1.6 | 4.2 | 1.39 | 2.60 | 0.53 |

### *3.2.3 Sensitivity analysis: Changes in parameter values*

The change of parameters associated to plant and animal products and fertilisers to the maximum and minimum values found in the literature caused a relative change of 26−29% in IN, TIN, TST, 10−15% in $TST_c$ and FCI and practically no change in the other indicators (Fig. 5A). Changes in the conversion coefficients (Table 3) altered the size of the N flows, and therefore all the indicators related to system size, activity and cycling. The change in $TST_c$ and FCI was different than for the other indicators because there are few cycling flows in the network, i.e. the change in $TST_c$ was relatively smaller than the change in TST. PL did not change as it depends on the number of activities which was not altered. The change in management parameters (Table 3) had a relatively greater effect on the integration indicators (TSTc, FCI and PL) (Fig 5 B) than the change in conversion coefficients of plant and animal products and fertilisers. PL changes because of the changes in TIN and TST. Management parameters determine the amount of N retained in the system resulting in a much larger effect on $TST_c$, FCI and PL (Fig. 5B).

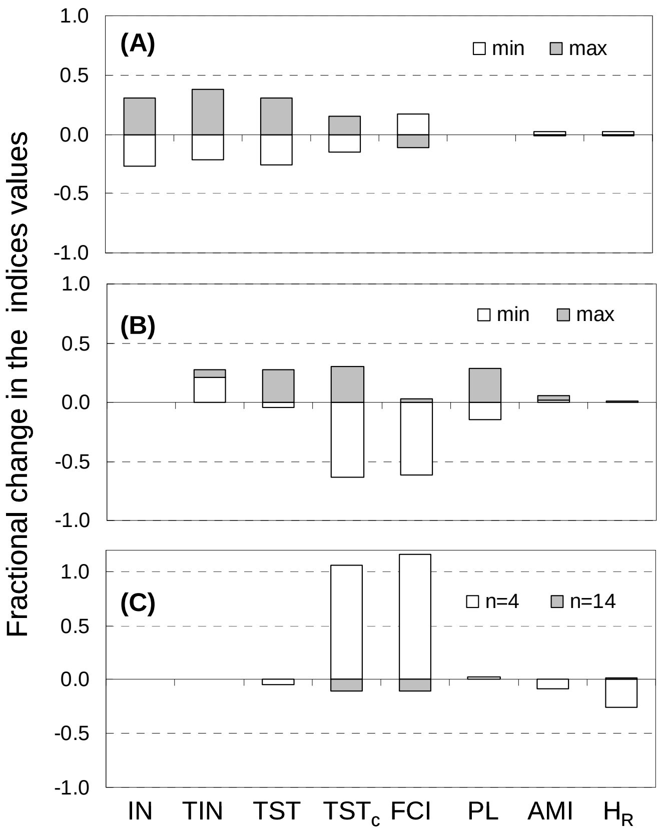



Figure 5: Fractional changes in the indicators IN, TIN, TST, TSTc, FCI, PL, AMI, and $H_R$ for three situations: (A) Changes in conversion coefficients for N concentrations, dry matter and energy values of plant and animal products; (B) Changes in management related parameters; (C) Changes in the indicator values as a result of aggregating (n=10) or disaggregating compartments (n=14) as compared to the baseline (n=12). The fractional changes refer to the observed values in Table 7.

*3.3.4 Sensitivity analysis: Conceptualisation of the system*

The conceptualisation of the system has a large effect on the cycling indicators ($TST_c$, FCI and PL) and on the structure/organisation related indicators (AMI, $H_R$) (Fig. 5C), and relatively no or little effect on the system size related indicators (IN, TIN and TST). By removing compartments, the amount of N cycled increases because we aggregate the flows of several compartments into one. The total flow in the system does not change due to the aggregation, and therefore the largest effects are observed in $TST_c$ and FCI. The aggregation also had an effect on the diversity of N flows because the indicator sums the contribution of each compartmental flow to obtain the system diversity.

# 4. Discussion

In order to study N flows within agro-ecosystems the relevant sub-systems or compartments need to be identified (Hirata and Ulanowicz, 1986). The question which elements should be aggregated into a compartment and how to conceptualise the structure of the system is difficult to answer. Aggregation with no loss of information is not possible, but one could aim at minimising loss of observed outputs. The risk of aggregation is that the elements of the system become black boxes. We acknowledge that the NA is sensitive to the system definitions, a common problem of systems analytical tools to study ecological systems (Fath et al., 2007), and even more so in the agro-ecosystems studies where biophysical and socioeconomic aspects interact (Stomph et al., 1994). Clearly defining system boundaries and the aim of the study are imperative, and this may allow comparison across systems and most likely also across sites.

Results of the NA are also sensitive to changes in parameters values (conversion coefficients), but this can be addressed by improving the accuracy of parameters and flows size estimations. In any analysis technique, the accuracy of the results is as good as the data available (Fath et al., 2007). Estimation of flows (e.g. feed intake from grasslands, crop residues removal from fields) and system processes represent a major challenge, one in which we can build experience, and should not prevent us from using NA to characterise the integration of agro-ecosystems. The size and the structure of the N flows in the network are sensitive to management, and therefore the indicators of integration reflect changes in management and can be used to assess those changes and compare with other farm system productivity indicators.

The indicators of organisation are useful to compare diversity across farm household systems. AMI and $H_R$ provide information on the configuration of the network of flows resulting from the management by the farm household. This measure of diversity of N flows can be used to compare systems within a region but also across environments. AMI will approach its upper boundary when N flows approach their most efficient configuration for a given system size (T..). Using NA the impact of technologies aimed at intensifying crop or livestock production on the whole farm household can be evaluated *ex post*, in terms of integration and dependency of external inputs. This allows to assess properties that are otherwise not evident from direct observation or measurements from individual compartments of the system, and offers opportunities to test configurations of flow patterns resulting in more efficient use of resources, which may be confronted with economic indicators.

NA seems useful to evaluate integration and diversity of different farm household systems. The indicators showed that the farm households were different in size (TST), but equally small in recycling and dependency on large N imports from common pastures to support livestock production. In general, N cycling indicators of agro-ecosystems are much lower than those calculated for natural ecosystems (Finn, 1980) since the principal aim of agro-ecosystem is to produce food and other goods that are exported. Differences in organisation of the flows and diversity were not large among the three farm types; although we observed a trend from poor to wealthier suggesting that the poor in this environment have more difficulties for spread risk. On-farm production of fodder crops could substitute or supplement the feeding from common pastures, and add to the opportunities to increase recycling. However, household objectives and limitations imposed by other farm resources (e.g. labour constraints) determine whether this strategy could improve integration.

In the case study, collected excreta contributed to the manure heap, but urine from livestock was mostly lost reducing the amount of recycled N ($TST_c$). Fertilisers used for cropping apart from mineral fertilisers, included household waste and (a part of) human excreta. Both N sources contribute to the recycled N ($TST_c$) and the cycling index of the systems (FCI). The number of animals largely determined the amount of imported N, because most of the feed requirements were met with grass from communal grazing land. Wealthy and medium households imported relatively large amounts of N for feeding livestock, but at least half of the N excreta is left in the common pastures. The amount of recycled N could increase considerably if the animals were fed with fodder produced on-farm, but this may compete for land, labour and other resources.

Low external agriculture where farmers have no or limited access to external inputs should aim at integrated farm household systems which use nutrients efficiently and reduce the dependency on external inputs. Especially in marginal environments, where the provision of external inputs is uncertain, e.g. because of market instability, recycling nutrients for crop and livestock production is a viable farm household strategy. In such agro-ecosystems cycling may help increasing adaptability and reliability (López-Ridaura et al., 2002).

### 4.3 Future research

NA can be used to compare farm household systems across environments. In this study the farm household system was the unit of analysis but NA may be applied at other aggregation levels (e.g. village or watershed), requiring a different conceptualisation of the system. In the quantification of N flows within the farm household systems we did not include losses of N through leaching, and gaseous losses. Provided data is available these flows can be included in the NA, although estimation of their importance is highly problematic (Faerge and Magid, 2004). Linking integration indicators with farm economic indicators may assist the identification of synergies and trade-offs and the design of more resource use efficient and robust farming systems. Evaluating the relative importance of different flows into and within the systems by including the concept of 'ascendency' (Ulanowicz, 1997), an indicator to systems adaptability will be the focus of further research.

## 5. Conclusions

NA provides a method to analyse the degree to which household activities are integrated. Diversity of farm household activities does not necessarily lead to integration of these activities through increased exchange of resources (i.e. N). N cycling indicators of agro-ecosystems are much lower than those calculated for natural ecosystems due to export of food and other goods from the agro-ecosystems. Consequently, large amounts of N are withdrawn from the system resulting in relatively few opportunities for recycling and associated low cycling indicators. However, increased N cycling in agro-ecosystems may reduce total N inflow and thus the dependency on external inputs. Conceptualising and measuring processes and flows remain a major challenge in (agro)-ecosystems studies, but this should not prevent us from applying NA that assist us in quantifying integration and diversity of agro-ecosystems. Network analysis could provide the means of testing hypotheses that relate diversity and integration to sustainability.

Chapter 6

# Characterisation of N flows and cycling in smallholder crop-livestock systems of the highlands of East and southern Africa through network analysis[†]

[†] Parts of this chapter were presented as:
Rufino, M.C., P. Reidsma, S. López-Ridaura and P. Tittonell, 2008. Network analysis to assess the productivity and resilience of complex agro-ecosystems. Oral presentation at the GECAFS Conference: Food Security and Environmental Change: Linking Science, development and policy for adaptation, held at Oxford, UK, 2-4 April 2008. Book of abstracts.

and is summary from:
Rufino, M.C., P. Tittonell, P. Reidsma, S. López-Ridaura, H. Hengsdijk, K.E. Giller and A. Verhagen. Characterisation of N flows and cycling in smallholder crop-livestock systems of the highlands of East and southern Africa through network analysis, Submitted.

## Abstract

Smallholder farming systems in Sub-Saharan Africa are often nutrient-limited systems. Because farmers largely rely on the use of natural resources, it has been stated that the inflows of nutrients to the systems should be increased to compensate for exports and losses, while increased integration through internal recycling may increase the efficiency of nutrient utilisation. To explore to what extent the properties of nutrient cycling networks relate to the capacity of the systems to sustain rural families, we investigated the characteristics of N flows and cycling in contrasting African crop-livestock systems by using concepts form ecological network analysis (NA). The case studies included farm households from different social strata at three sites: Tigray in northern Ethiopia, Kakamega in western Kenya and Murewa in Zimbabwe. These farm households were conceptualised as networks, in which the compartments were the household and the different farming activities, and the N flows were the connections between the compartments. Indicators were used to assess network size, activity and cycling, and the organisation and diversity of the N flows which were compared to measures of system performance: biomass productivity and food self-sufficiency. Systems in Tigray used about three times more N *per capita* than the systems in Kakamega, and 1.5 times more than Murewa. The amounts of N cycled were small and comparable at all sites (less than 3.5 kg N *per capita* per year). Dependency on external inputs to sustain current production was larger for poor than for wealthier households, who had larger soil N storages *per capita*. Poor households did not achieve food self-sufficiency at any of the three sites. The measures of system performance were positively related to the size of the network of N flows and to the organisation and cycling, but the efficiencies of utilisation were different across the sites in relation to the size of soil storages and the importance of livestock to the N flows of the system. The use of network analysis of N flows to account for resource allocation and configuration of the farm household system appears promising to assess systems agro-ecosystems properties by looking at dependency on the external environment for biophysical inputs and the internal organisation of the system. Because increases in size of the network of N flows and organisation of the flows lead to increases in productivity and food self-sufficiency and also reduce dependency, combination of both strategies may benefit not only productivity but also adaptability and reliability of smallholders crop-livestock systems.

**Keywords:** Diversity, resource use efficiency, integration, farming system analysis

## 1. Introduction

Beyond the diversity of livelihood strategies that may be observed among rural households in Sub-Saharan Africa, their subsistence relies largely on the use of natural resources. Crop-livestock interactions, in particular, play a major role in defining the degree of integration through flows of biomass, nutrients and labour between farm activities (McIntire et al., 1992). Nutrients enter the farming system mostly via livestock or agricultural inputs, and transfers take place among the different compartments of the system, such as the different cropping and livestock units and the household. Many of such transfers are the deliberate result of human agency. The diversity of system compartments (or 'activities'), their integration, and the magnitude of the nutrient flows are largely the result of farmers' management decisions. We hypothesised that these, together with the context in which they operate (i.e., agro-ecology, demography, markets), have a strong influence on the farm productivity.

Smallholder farming systems in Sub-Saharan Africa are often nutrient-limited systems. Continuous cropping without restitution of carbon and nutrients to the soil has led to severe degradation of soil fertility in vast areas of Africa (Sanchez, 2002), and integrated nutrient management (INM) has been advocated as one of the most promising strategies to restore soil fertility and improving resource use efficiency (Vanlauwe et al., 2002). Although it is broadly recognised that the inflows of nutrients to the systems should be increased to compensate for exports and losses (see Smaling et al., 1999) the efficiency of nutrient use depends largely on the recycling capacity of the system (Van Noordwijk, 1999). This is particularly the case for N, which is used in large amounts by crops, animals and humans and is highly prone to dissipations from the agro-ecosystem (Giller et al., 1997). Measures to promote INM in smallholder farming systems must be designed considering their characteristics in relation to the size and organisation of their nutrient flows, seeking entry points to improve nutrient use efficiencies.

We investigated the characteristics of N flows and cycling in contrasting African crop-livestock systems using concepts form ecological network analysis (Fath and Patten, 1999; Ulanowicz, 2001), and related them to system performance. N flows and cycling were characterised relying on the assumption that elements from ecosystem theory can be applied to the study of agro-ecosystems (Rufino et al., 2008a - Chapter 5). Network analysis (NA) is an input-output analysis originally developed in economics by Leontief (1951; 1966) to estimate the amount of raw materials to produce a certain quantity of goods and it was introduced into ecology by Hannon (1973). NA can be applied to many disciplines in which the systems can be conceptualised as networks of interacting compartments exchanging inputs and outputs (Fath and Patten, 1999). Such exchanges represent resource flows, which may refer to physical inputs such as energy, biomass and nutrients, and a series of indicators are calculated to assess their size, integration, diversity and organisation. Our main guiding question was to what extent such properties of nutrient cycling networks relate to the capacity of smallholder crop-livestock systems to sustain rural families. The objective was to study the network size, integration, organisation and diversity of N flows within contrasting crop-livestock systems and their relation to system productivity and to the household food self-sufficiency.

# 2. Materials and methods

## 2.1 Network analysis

A farm household is conceptualised as a network in which the nodes are compartments defined to represent resource allocation by the household, and include the different crop fields (cropping activities), the livestock units (livestock activities), the organic resource management activities (composting activity), and the household (including the family members). A system is then defined by its compartments ($H_i$), the change in their storage ($x_i$), the inflows ($z_{io}$) and outflows ($y_{oi}$) between the compartments and the external environment, and the internal flows between compartments (e.g., $f_{ij}$ represents an internal flow from $H_j$ to $H_i$). Figure 1 illustrates the simplest network, a system with two compartments, $H_1$ and $H_2$, for which the storages $x_1$ and $x_2$, and the flows $y_{01}$, $z_{01}$, $f_{12}$, $f_{21}$, $y_{02}$ and $z_{20}$ may be identified. In this analysis we expressed flows in kg N $y^{-1}$, and storage and compartmental size in kg N.

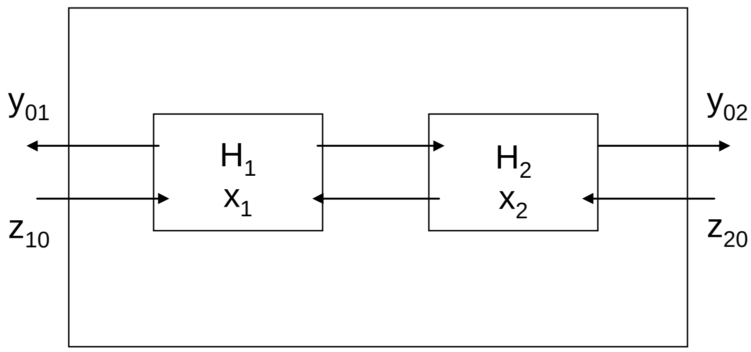



Figure 1: System representing a network with two compartments $H_1$ and $H_2$, and their respective storages $x_1$ and $x_2$, the internal flows $f_{12}$ and $f_{21}$, and exchanges from $z_{10}$ and $z_{20}$ and to the external environment, i.e. $y_{01}$ and $y_{02}$. The rectangular box defines the system boundaries. Source: Finn (1980).

For N flows from one compartment (j=0..n) to another (i=1…n, n+1, n+2), n+1 accounts for usable exports (e.g. grain, milk) and n+2 accounts for unusable exports or dissipations (e.g. animal excreta left in the communal grasslands) (Hirata and Ulanowicz, 1984). A compartment j=0 was defined to keep track of the imports. Storage in livestock compartments is an estimation of the amount of N contained in the animal mass (kg N), while for crop field compartments storage is an estimation of the amount of N contained in the 0.3 m top soil layer (in kg N). We selected a number of NA indicators to characterise the size, integration, diversity and organisation of the networks of N flows (Table 1), as discussed in detail in Chapter 5.

Table 1: Indicators used in the network analysis of N flows in agro-ecosystems and their calculation.

| Indicator | Calculation | | Reference |
|---|---|---|---|
| **(Section 2.1.1)** | | | |
| Imports | $IN = \sum_{i=1}^{n} z_{io}$ | (Eq. 1) | |
| Total Inflow | $TIN = \sum_{i=1}^{n} z_{io} - \sum_{i=1}^{n} (\dot{x}_i)_-$ | (Eq. 2) | Finn (1980) |
| Compartmental Throughflow | $T_i = \sum_{j=1}^{n} f_{ij} + z_{io} - (\dot{x}_i)_-$ | (Eq. 3) | |
| Total System Throughflow | $TST = \sum_{i=1}^{n} T_i$ | (Eq. 4) | |
| Total System Throughput | $T.. = \sum_{i,j=1}^{n} T_{ij}$ | (Eq. 5) | Patten and Higashi (1984) |
| Finn's Cycling Index | $FCI = \frac{TST_c}{TST}$ | (Eq. 6) | Finn (1980) |
| Dependency | $D = IN / TST$ | (Eq. 7) | |
| **(Section 2.1.2)** | | | |
| Average Mutual Information | $AMI = k \sum_{i=1}^{n+2} \sum_{j=0}^{n} \frac{T_{ij}}{T..} log_2 \frac{T_{ij} T..}{T_{i.} T_{.j}}$ | (Eq. 8) | Ulanowicz (2001), Latham and Scully (2002) |
| Statistical uncertainty (Diversity) | $H_R = - \sum_{j=0}^{n} \frac{T_{.j}}{T..} log_2 \frac{T_{.j}}{T..}$ | (Eq. 9) | |
| **(Section 2.1.3)** | | | |
| Biomass production | $B = \sum_{i=1}^{n} \frac{Yield}{HI}$ | (Eq. 13) | |
| Apparent conversion efficiency | $CE = \frac{B}{IN}$ | (Eq. 14) | |
| Food self-sufficiency ratio | $FSSR = \frac{\sum_{i=1}^{n} EY_i}{ER\_household}$ | (Eq. 15) | |

Notation: $z_{io}$ are N inflows to each system compartment ($H_i$) from the external environment, $x_i$ represents the change in storage of a compartment and $f_{ij}$ represents internal flows between compartments (e.g., from $H_j$ to $H_i$), HI is the crop specific harvest index, EY is the edible yield converted into energy units, and ER_household is the energy requirement of the household.

### *2.1.1 Indicators of network size, activity and integration*

Indicators to assess network size, activity and integration in agro-ecosystems were derived from the flow analysis in ecosystems by Finn (1980) (Table 1). Imports (IN) is the amount of N that is imported from the external environment into the system (Eq. 1). Total inflow (TIN) into the system is the sum of N flows from external inputs (z) into all compartments ($H_{i,..,n}$) plus the amount of N contributed to the system total flows by the storage of all compartments $(\dot{x}_i)_-$, i.e. the negative changes in the storage (Eq. 2). The compartmental throughflow ($T_i$) is the sum of all flows coming into compartment $H_i$ from other compartments ($f_{ij}$) and from the exterior (z), minus the N outflows from compartment $H_i$ (the negative changes in storage $x_i$) (Eq. 3). The total system throughflow (TST) is the sum of all compartmental throughflows ($T_i$) in the system (Eq. 4), and it represents the mobile N pool in the system associated with the system's actual production (activity). The total system throughput (T..) is the sum of all inflows and outflows of N to and from all the compartments of the system (Eq. 5), representing the total size of N flows. The Finn's cycling index (FCI) is the proportion of TST that is recycled within the system (Eq. 6), and was proposed to be used to assess the degree of integration in agro-ecosystem (Rufino et al. 2008a - Chapter 5). To calculate FCI, it is first necessary to estimate the relative cycling efficiency for each compartment, which is the ratio between internal inflows:outflows to and from all system compartments. The total cycled system throghflow ($TST_c$) is sum of all the weighted relative cycling efficiencies in the system. The FCI takes values between 0 and 1 (or 0−100%), with these extremes indicating either no recycling or complete recycling. The dependence of the system on external inputs (D) is calculated as the ratio IN / TST (Eq. 7).

### *2.1.2 Indicators of organisation and diversity*

Two measures are used to assess the organisation and diversity of the network connections (Table 1). These measures that come from communication theory are the average mutual information (AMI) and the statistical uncertainly ($H_R$) (Latham and Scully, 2002). AMI quantifies the organisation of the flows in the network (Eq. 8), measuring the flow of information associated with the exchange of material within the system. The log term of Eq. 8 calculates the conditional probability that a flow entering $H_i$ came from $H_j$. That probability is the fraction of the flow $f_{ij}$ to all flows that enter $H_i$, divided by the product of the fractions of $T_i$ and of $T_j$ to the total system throughput T... Each of these conditional probabilities are weighted by the joint probability of that flow ($T_{ij}$/T..), and these weighted 'constraints' are summed over all combinations of i and j in the network. In a system where the total flow is divided equally among all the compartments, and all the compartments are connected, AMI will be 0 or very close to 0. If a few flows, which are a large proportion of T.., connect a few compartments, the value of AMI will approach its upper bound. In natural ecosystems for which it has been estimated AMI typically takes on a narrow range of values, from 0 to ca. 6 (Patten, 1995). $H_R$ is the upper bound for AMI, and represents the diversity of flows given a certain amount of throughput (T..) (Eq. 9). When the contribution of the flow out of a compartment (represented by $T_{.j}$ in Eq. 9) to total throughput (T..) is small and different across compartments, diversity increases, i.e. the pattern of flows in the network deviates from being equally sized flows. $H_R$ increases when T.. is partitioned among a greater number of flows. Both AMI and $H_R$ are measured in bits, which relates to the concept of binary decisions; one bit represents one binary decision. For more detail on AMI and its derivation we refer to Latham and Scully (2002).

### *2.1.3 Indicators of productivity and efficiency*

Total biomass production (kg DM per farm) was calculated as the sum of aboveground biomass (= yield of harvestable parts / harvest index) measured at each field cropped by the household (i.e., this includes food, fodder and cash crops but not communal grasslands) (Eq. 13). The ratio between total biomass production and IN (Eq. 14) was calculated as a rough measure of the capacity of the system to convert N inputs into biomass (CE=conversion efficiency). Food self-sufficiency was calculated as the ratio (FSSR) between energy in the food produced on farm and energy requirements by the household (Eq. 15). We converted the harvested product destined to self-consumption into energy equivalents using standard values of energy content in food products (USDA Nutrient Data Laboratory, 2007), and estimated household energy needs using an average of 9 MJ per day *per capita* (Bender, 1997).

## 2.2 Case studies

The analysis included smallholder crop-livestock systems from three case study sites in highland areas of Sub-Saharan Africa: Teghane village (13° 45’N, 39° 41’E) in Tigray, northern Ethiopia; Chiwara village (17°51’S, 31° 49’E) in Murewa, north eastern Zimbabwe; and Mutsulio village (0° 12’N, 34° 48’E) in Kakamega, western Kenya (Table 2). In the three sites smallholder subsistence crop-livestock systems predominate (0.5−3.0 ha in size), with cereals as staple food. The sites differ in population density, agro-ecological potential (rainfall and soils) and the relative importance of cattle, with Kakamega at one extreme receiving the highest annual rainfall, having the highest population density, and the smallest number of livestock per household, and Tigray at the other extreme with the lowest annual rainfall, the largest herds and a population density comparable to that of Murewa. Whereas the relatively rich soils and good climate of Kakamega allow growing cash crops such as tea and coffee, steep slopes, stony soils, frost risk and rainfall limited to a short period of the year constrain agricultural production in Tigray. A major difference between sites resides also in the type of livestock feeding system, which is based on grazing of communal pastures in Tigray and Murewa *vs* the cut-and-carry system (zero grazing) in Kakamega. In all cases livestock are fed crop residues and their manure is used to fertilise crops.

Table 2: Main biophysical and socioeconomic characteristics of the crop-livestock systems analysed.

| | Tigray (N Ethiopia) | Murewa (NE Zimbabwe) | Kakamega (W Kenya) |
|---|---|---|---|
| Altitude (masl) | 2700–2900 | 900–1400 | 1400–2000 |
| Temperature (˚C) | 18–21 | 18–23 | 18–22 |
| Rainfall (mm) | 540 (270–810) | 830 (750–1000) | 1990 (1750–2100) |
| Rainy season(s) | Unimodal (3 months) | Unimodal (5 months) | Bimodal (10 months) |
| Topography | Very undulating (escarpments) | Gently undulating | Moderately to very undulating |
| Soils (FAO) | Leptosols, Luvisols and Cambisols | Lixisols and Luvisols | Nitosols, Ferrasols and Acrisols |
| Range in soil clay + silt fraction (%)* | 35–90 | 8–15 | 60–80 |
| Area of land holdings* (ha) | 0.3–2.4 | 0.5–4.2 | 0.5–2.2 |
| Population density* (Inhabitants km$^{-2}$) | 128 | 104 | 650 |
| Distribution of household wealth classes* | Poor 60%; Medium 29%; Wealthier 11% | Poor 56%; Medium 28%; Wealthier 16% | Poor 55%; Medium 35%; Wealthier 10% |
| Livestock heads per household* | 2−10 | 1−5 | 1−2 |
| Main crops | Barley, wheat, field peas, faba beans, buckwheat, teff and prickly pears | Maize, groundnut, sweet potatoes, sunflower and vegetables | Maize, sorghum, beans, cowpea, tea, coffee, sugarcane, sweet potatoes, cassava, fruit trees and vegetables |
| Livestock system and composition | Free ranging and herded in communal grasslands; Zebu cattle (mainly Boran), sheep, donkeys, mules and chicken | Free ranging and herded in communal grasslands; Zebu cattle (Mashona, Africander), goats, sheep and chicken | Stalled or tethered on farm (cut and carry); Zebu cattle (mainly Boran), and crossbred Holstein, goats, sheep, chicken |

*At the specific locations considered

Household surveys were conducted at the three sites to collect information on family composition, land use and resource endowment (in 2002 at Tigray, 2002/3 at Murewa, and 2002 at Kakamega). Households at the three sites were categorised according to their resource endowment into poor, medium and wealthier households using site specific criteria and thresholds, such as area farmed, livestock owned, food security, labour availability, market orientation or access to off-farm income. At each site, a sub-sample of case study farms was selected to represent each of the three wealth categories indentified. These farms were characterised in detail, through delineation of resource flow maps (input use, resource allocation, production and marketing), soil sampling and laboratory analysis, crop yield and livestock production estimations and labour calendars. The detailed information obtained allowed us to quantify N stocks (in soils and animals) and flows to, from and within the systems to conduct the network analysis. We focused on the flows that are managed by the household. Further information on the household surveys, typologies and methodologies for detailed characterisation can be found for Tigray in Assefa et al. (2007) and in Mulder (2003); for Murewa in Zingore et al. (2007) and Tittonell et al. (2005b) for Kakamega.

### 2.3 Data processing

We constructed the N flow networks for 9 selected farms, representative of each wealth class at each site, and calculated the indicators described in Table 1. The resource flows obtained from the field assessments were converted into the common currency 'kg N' by using conversion coefficients from literature (e.g. N content in different crops and crop parts, in manure, in food, etc.) as explained in detail in Chapter 5. Four types of flows were defined: internal transfers, inflows and outflows from and to the external environment (imports and exports), and dissipations (e.g. amounts of material that cannot be re-used). In NA of natural ecosystems (forest, marine estuaries, etc.) indicators are usually expressed as amounts of matter (e.g., g or kg) per unit of time (e.g., year) and per unit of area (e.g., $m^2$). Here, we normalised the measures of flow size organisation on a *per capita* basis (kg N *per capita* $y^{-1}$) considering the number of family members per household. We chose not to normalise per area to avoid comparing measures that would be out of proportion across household wealth classes and environments. For instance, inflows of N by a head of livestock would yield widely different normalised indexes for a farm of 0.3 ha *vs* one of 1 ha.

The intake of N from grazing was considered as an inflow to the farm household system, and the excreted N dejected on off-farm was considered an outflow. Intake and excretion of the livestock was estimated for Tigray using a simple livestock model from the NUTMON toolbox (Vlaming et al., 2001) that uses as inputs animal type, animal size, grazing time and feed availability in the pasture, and feed supplemented on farm. Because complementary and more detailed information on livestock feeding, and livestock management was available for the case studies at Murewa (Dury, 2007) and Kakamega (Castellanos-Navarrete, 2007), estimations of livestock intake and excreta were made using the dynamic model LIVSIM (Rufino et al. 2007a - Appendix 1). For the cropping activities flows were derived from yields and biomass production estimated from harvest indices. We included a compartment representing the management unit used to recycle animal manures and the composting of other organic residues. From the detailed characterisation of farm households we derived the type and amount of all farm produce that was consumed by the family or sold, and the type and amount of food items purchased on the market. Soil N storage was calculated for the top 0.3 m layer using measurements of total soil N and bulk density.

The analysis focused on N flows that are more closely linked to management decisions, under direct control by farmers, such as the inflow of N via fertilisers or food and the outflows to the market in harvested products. Due to lack of information, and to avoid introducing error by using generic pedo-transfer functions (e.g. Van den Bosch et al., 1998), we did not estimate the value of indirect flows such as N leaching, volatilisation, runoff, wet deposition, $N_2$-fixation or redistribution of sediments in the landscape. The omission of these flows may modify the calculated contribution from and to the soil N storage, or the net N loss to the environment. Estimates for these indirect N inflows and outflows using pedo-transfer functions for Kakamega yielded a net partial balance (= indirect inputs – indirect outputs) of c. –10 kg N ha $y^{-1}$ on average (Tittonell et al., 2006).

## 2.4 Assumptions

We assumed that each individual field that farmers manage was a different farming activity (each a different network compartment), which may have clearly delimited boundaries (e.g. hedges) or relatively uniform soil properties in the arable layer. These fields included sole crops, intercrops or combinations of annual and perennial crops. The livestock compartments consisted of individual or groups of animals that were managed as a unit. The definition of the system under study (i.e., number and type of compartments to be considered and their interactions) has a decisive impact on the configuration of the network and the value of some of the indicators calculated (cf. Table 1). For instance, defining each field plot as a system compartment, or defining each crop type as a system compartment, yields different results (cf. Chapter 5). We chose for the former approach, which represents ‘management units’ more closely.

Further, when the amount of food indicated by farmers as produced plus purchased was not sufficient to cover the average energy needs *per capita*, we assumed the difference to be fulfilled by extra amounts of the staple cereal at each site. This energy deficit may have been covered with purchased food, received donations, food aid or other sort of assistance by family, the community or other organisations. Finally, this study represents a snapshot of the systems in time, and results should be interpreted taking into account that these systems are dynamic.

# 3. Results

### 3.1 Characteristics of the systems and their N flows

The smallholder crop-livestock systems analysed differed in the area of land cropped per household and in their land:labour ratio, with Murewa (Zimbabwe) exhibiting larger areas of land available per family member (Table 3).

Table 3: Characteristics of the crop-livestock systems analysed and the major N inflows and soil N storage.

| Site/ wealth class | Family size (#) | Cropped area (ha) | Land/ labour (ha capita$^{-1}$) | Livestock owned (TLUs) | Fertiliser N (kg ha$^{-1}$) | Feed N imported (kg TLU$^{-1}$) | Food N imported (kg capita$^{-1}$) | Soil N storage (kg ha$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| Tigray | | | | | | | | |
| Poor | 5 | 0.3 | 0.06 | 1.2 | 23.3 | 70.2 | 3.2 | 7830 |
| Medium | 9 | 0.7 | 0.08 | 7.1 | 3.7 | 50.4 | 3.1 | 5330 |
| Wealthier | 10 | 2.4 | 0.24 | 10.0 | 10.2 | 56.6 | 0 | 5470 |
| Murewa | | | | | | | | |
| Poor | 4 | 0.9 | 0.23 | 0.3 | 20.9 | 0 | 2.1 | 1750 |
| Medium | 6 | 2.1 | 0.37 | 4.8 | 33.7 | 15.4 | 0.3 | 2090 |
| Wealthier | 6 | 2.5 | 0.42 | 5.4 | 33.4 | 18.1 | 0.3 | 2050 |
| Kakamega | | | | | | | | |
| Poor | 6 | 1.0 | 0.17 | 0 | 4.9 | 0 | 1.9 | 4880 |
| Medium | 5 | 2.4 | 0.48 | 2.0 | 4.3 | 3.6 | 0.4 | 5770 |
| Wealthier | 9 | 2.9 | 0.32 | 3.5 | 6.1 | 3.9 | 1.4 | 6180 |

Soil N storage calculated for the top 0.3 m soil layer.

Livestock densities (i.e., the ratio of number of heads to cropped area), were the largest in Tigray (Ethiopia) and the smallest in Kakamega (Kenya). The size and the main

type of N imports differed contrastingly between wealth classes and across sites. In Tigray, the main source of N imports was feed N, and this was largest in total for the wealthier farm household with more livestock, but the amount imported per animal (Tropical Livestock Unit, TLU) was larger for the farm household with less land and therefore smaller on-farm production of fodder (crop residues). In Murewa, feed N and fertiliser N both contributed equally to the total N imports for the wealthier farm households and only fertiliser N for the poorer households. The fertiliser N use was the highest in Murewa as compared to the other two sites. In Kakamega, the size of the imports was much smaller than in the other 2 sites, and the relative contribution of fertiliser N (expressed on a *per capita* basis) was as important as food N for the three types of farm households. Soil N storages differed widely across sites, with the largest stocks in the systems at Kakamega, followed by Tigray and Murewa.
The configuration of the networks of N flows for the 9 case study farms is illustrated in Figs 2, 3 and 4, where the actual structure of the networks was simplified for clarity. Food crops were grouped separately from fodder crops, and all animal compartments were grouped together to show the main internal flows in the farm household. In the calculations, however, we kept individual flows from and to each of the compartments. The number of flows was 24, 39 and 47, for poor, medium and wealthier farm households at Tigray, 21, 43 and 43 for poor, medium and wealthier farm households at Murewa, and 40, 54 and 65 for poor, medium and wealthier farm households at Kakamega. In all cases, the main sinks for N internal flows were the household and the livestock: food products from cropping and livestock activities were mainly consumed by the household and the residues of crops after harvest were fed to the livestock. Not all compartments could in practice be linked through N flows because not all farming activities produce outputs that can be recycled. For some farming activities, outputs were sold and therefore exported out of the system, with only a small proportion consumed by the household (e.g. tea, vegetables). Farmers usually selected their best fields to produce the crops that contributed the most to their total farm production and concentrated most inputs in these few good fields. The number of compartments increased from poorer to wealthier households, and the systems in Kakamega had a larger number of compartments than the other sites, due to the more diverse farming activities observed on these farms.

### 3.2 Size, integration, diversity and organisation of N flows

The N imports (IN), total N inflows (TIN), total system throughflow (TST) and total system throughput (T..) (cf. Table 1) calculated for the 9 case study farms indicate that

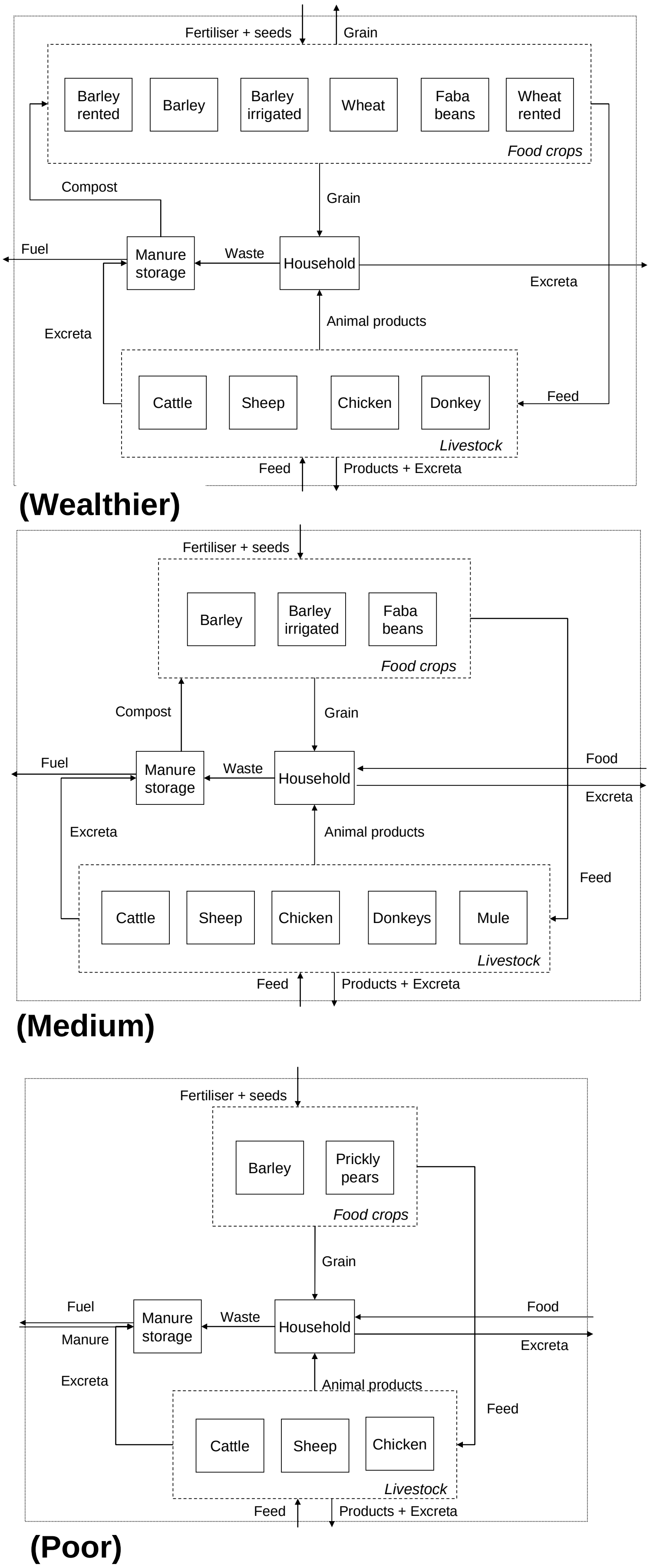



Figure 2: Schematic representation of the network of N flows for three different farm household types (wealthier, medium and poor) in Teghane, Tigray in the Northern highlands of Ethiopia. The boxes represent compartments conceptualised as farming activities or management units. The N flows are represented by the arrows between compartments and with the exterior and were simplified for clarity of the diagram.

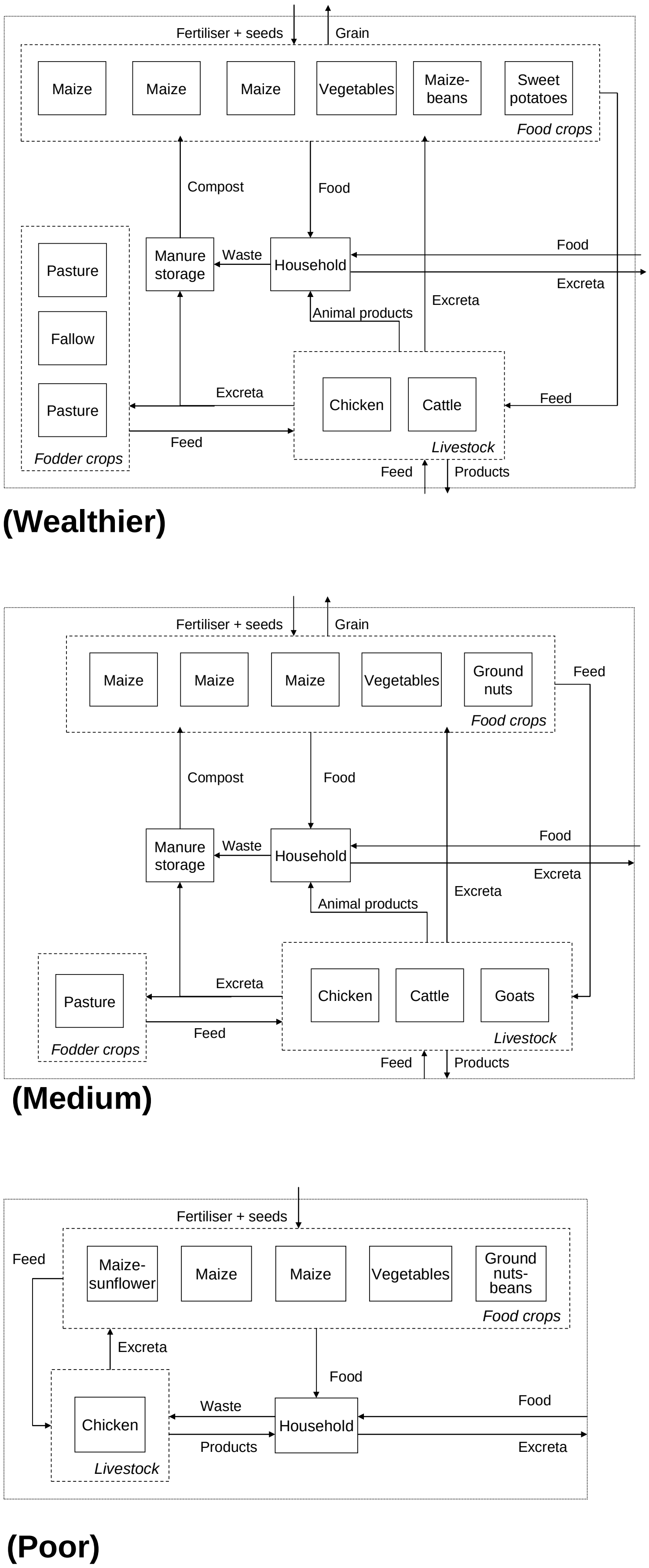
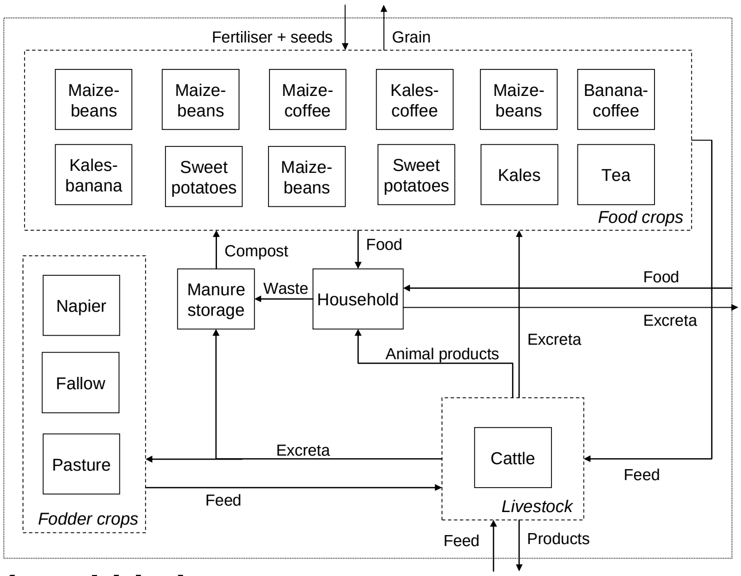
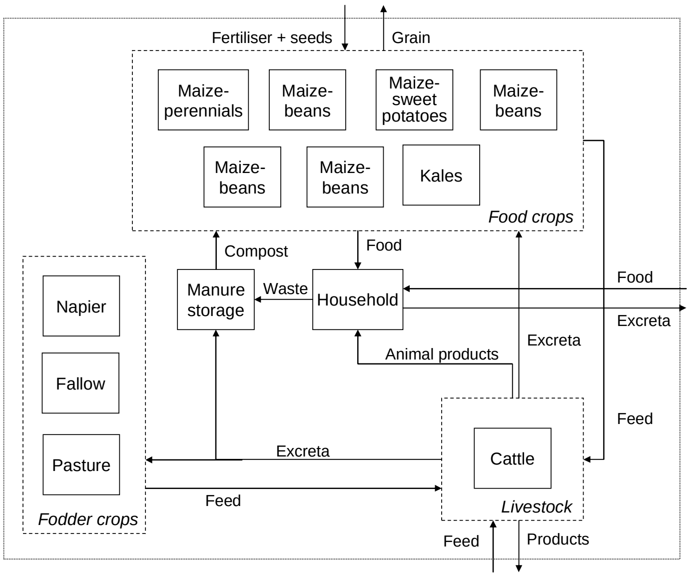


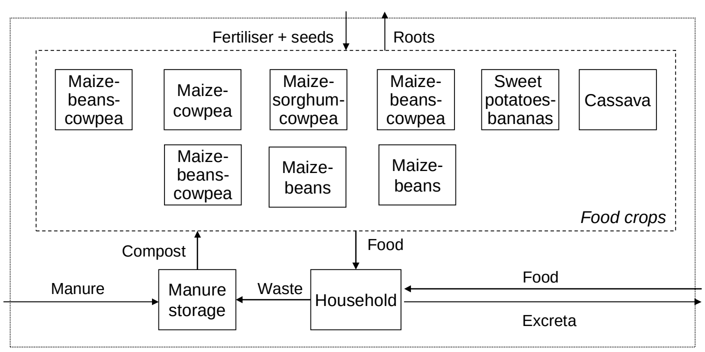

Figure 3: Diagrammatic representation of the network of N flows for three different farm household types (wealthier, medium and poor) in Chiwara, Murewa, NE Zimbabwe. The boxes represent compartments conceptualised as farming activities or management units (see Section 2.2 for more detail). The N flows are represented by the arrows between compartments and with the exterior and were simplified for clarity of the diagram.




**(Wealthier)**




**(Medium)**




**(Poor)**

Figure 4: Diagrammatic representation of the network of N flows for three different farm household types (wealthier, medium and poor) in Shinyanlu, Kakamega, western Kenya. The boxes represent compartments conceptualised as farming activities or management units (see Section 2.2 for more detail). The N flows are represented by the arrows between compartments and with the exterior and were simplified for clarity of the diagram.

the systems in Tigray used about three times more N per capita than the systems in Kakamega, and one and half times more than Murewa (Fig. 5). N imports and total inflow were on average larger in Tigray, leading also to larger differences between TST and T.. values. The largest difference between TST and T.. would be observed when the system is in a steady-state (when N imports equal N exports); small differences mean that the storage of the various compartments plays an important role in balancing out the system activity. A change in storage implies, for example, the loss or accumulation of nutrients in a certain compartment. In Kakamega there was almost no difference between TST and T.. implying that most N came from the storages. This can also be seen from the difference between IN and TIN (i.e., IN + nutrients taken from the storage).

Table 4: Indicators of dependence on external N imports, N cycling and size of N storage expressed *per capita.*

| Site/ Wealth class | D (IN / TST) | IN / TIN | $TST_{cycled}$ (kg capita$^{-1}$) | FCI (%) | Soil N storage (kg capita$^{-1}$) |
|---|---|---|---|---|---|
| Tigray | | | | | |
| Poor | 0.72 | 0.97 | 0.9 | 2.9 | 470 |
| Medium | 0.68 | 0.99 | 1.4 | 2.2 | 414 |
| Wealthier | 0.66 | 0.94 | 2.5 | 2.6 | 1312 |
| Murewa | | | | | |
| Poor | 0.65 | 0.90 | 0.1 | 0.9 | 393 |
| Medium | 0.54 | 0.83 | 1.6 | 3.5 | 765 |
| Wealthier | 0.45 | 0.77 | 3.4 | 5.5 | 1197 |
| Kakamega | | | | | |
| Poor | 0.45 | 0.78 | 0.1 | 2.2 | 814 |
| Medium | 0.12 | 0.24 | 3.0 | 9.3 | 3115 |
| Wealthier | 0.34 | 0.67 | 1.9 | 11.0 | 1991 |

At the three sites the relative importance of IN to TST, or dependency (D), tended to be greater for the poorer than for the wealthier farm households (Table 4). Most of the total N inflows in the systems consisted of N imports, as revealed by the IN to TIN ratios, with greater values in Tigray and Murewa than in Kakamega. The amounts of N cycled were small and comparable at all sites (less than 3.5 kg N capita$^{-1}$ y$^{-1}$). The differences between farm types within sites were larger than those across sites: wealthier farm households recycled between 2−3 kg, and the poorest less than 1 kg N capita$^{-1}$ y$^{-1}$. The degree of integration, measured with the Finn's cycling index (FCI) was relatively larger for the medium and wealthier farm households at Kakamega

(9−11%), due partly to the smaller values of TST as compared to Tigray and Murewa. Wealthier farm households had larger soil storages of N *per capita* than the poorer ones, and this together with more livestock explains the larger total system size and activity. The TST represented 7–15% of the total soil N storage *per capita* in Tigray, 2–6% in Murewa and barely 0.7–1% in Kakamega.

The values of the average mutual information (AMI) calculated for the nine case study farms indicated that the poor farm households have less organised networks of N flows compared to the wealthier farms at the three sites (Fig. 6). The values calculated for the statistical uncertainty ($H_R$), the upper bound of AMI and a measure of the diversity of flows, indicate a greater diversity in network connections for the wealthier than for

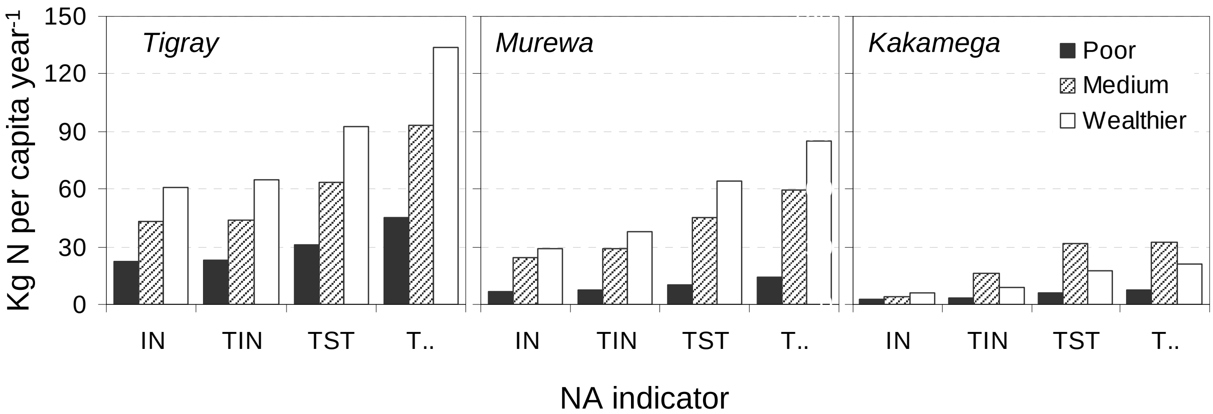



Figure 5: Network indicators (Imports (IN), Total inflow (TIN), Throughflow (TST), and Throughput (T)), calculated for different types of farm households at three sites: Tigray in the Northern Highlands of Ethiopia, Murewa in NE Zimbawe, and Kakamega in western Kenya. See text in Section 2.1.1 and Table 1 for details.

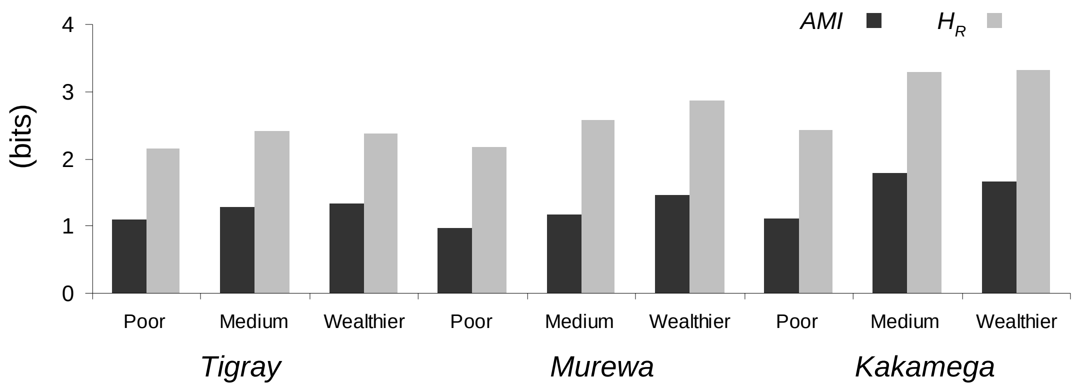



Figure 6: Indicators of organisation, average mutual information (AMI) and, diversity ($H_R$) for three different household types (wealthier, medium and poorer) at three different sites: Tigray in Northern Ethiopia, Murewa in NE Zimbabwe and Kakamega in western Kenya. See Section 2.1.2 and Table 1 for details.

the poorer farms. The systems in Kakamega had a greater diversity of N flows compared with the other sites, indicating more choices for N flows – i.e., the actual N flows were associated with a more organised pattern than in the other two sites (Fig. 4). For all case study farms at the three sites the ratio $AMI/H_R$ ranged between around 0.44 and 0.56.

### 3.3 Systems productivity and efficiency

Biomass production *per capita* was comparable across sites, with the poorest households producing less than the wealthier (Table 5). The productivity (expressed in biomass) of the systems per unit of N imported, or the apparent N conversion efficiency, was the largest in Kakamega (2 to 30 times larger than at the other sites). This is also evidenced by the steeper relationships between N imports and biomass production for the Kakamega systems in Fig.7A, with slopes of 15, 83 and 242 kg DM kg $N^{-1}$ imported for Tigray, Murewa and Kakamega, respectively. The systems at Murewa produced, on average, more edible energy *per capita* than at the other two sites (Table 5). The poorest households did not achieve food self-sufficiency in any of the three sites. The medium class at Tigray and the wealthier at Kakamega did not produce enough food on their farms to fulfil the family energy requirement, but accessed cash through selling farm products that was used to cover the food deficit.

Comparing indicators of NA with system performance, we observe that the larger the value of the Finn's cycling index (FCI) the greater the production of biomass *per capita*. The relationship differs across sites, with less biomass produced per unit FCI at Kakamega (Fig. 7B). This, together with the greater apparent conversion efficiency of imported N (Fig. 7A), indicates that more internal cycling (including mobilisation from the soil storage) sustains biomass production in the systems at Kakamega. The systems at Tigray and Murewa cycled less N and required larger N imports per unit of biomass produced. Next, we compared the relationships between the size of the network of N flows (T..) and their organisation (AMI) with the food self sufficiency ratio (FSSR) across the three sites. The wealthier households at Tigray met their energy demand (FSSR > 1) with larger N flows than at the other sites (Fig. 7C). The relationships between network organisation and FSSR (Fig. 7D) were comparable with the ones observed between FCI and biomass production, with the systems at Kakamega exhibiting a more sophisticated organisation of N flows.

The intensity of utilisation of N resources and the flow patterns differed across systems (Fig. 8A). The systems at Tigray, and particularly those at Murewa, utilised larger N throughputs (T..), and sustained production on smaller soil N stocks than at Kakamega. The systems in Kakagema largely relied on soil N storage, and less biomass was produced per unit of soil N storage (Fig. 8B). The differences in T.. across sites were related to differences in the size of the livestock N storage (size of the herd), and this relation between both was approximately 1:1 across sites (Fig. 8C). Larger herds at Tigray resulted in larger N inflows that are used (partly) to sustain production, with consequently less biomass produced per unit of livestock N storage, and presumably larger dissipations of the imported N.

Table 5: Indicators of system productivity and household food self-sufficiency.

| Site/ wealth class | Biomass production | N conversion efficiency | Food produced | Food self-consumed | FSSR[1] |
|---|---|---|---|---|---|
| | ($t\ capita^{-1}\ y^{-1}$) | ($kg\ dm\ kg\ N^{-1}$) | ($GJ\ capita^{-1}\ y^{-1}$) | ($GJ\ capita^{-1}\ y^{-1}$) | - |
| Tigray | | | | | |
| Poor | 0.5 | 23 | 1.4 | 1.4 | 0.4 |
| Medium | 0.5 | 12 | 2.0 | 2.0 | 0.6 |
| Wealthier | 1.1 | 18 | 5.6 | 3.4 | 1.7 |
| Murewa | | | | | |
| Poor | 0.3 | 44 | 1.5 | 1.4 | 0.5 |
| Medium | 1.6 | 66 | 8.4 | 3.9 | 2.2 |
| Wealthier | 2.5 | 86 | 11.2 | 2.9 | 3.4 |
| Kakamega | | | | | |
| Poor | 0.2 | 74 | 1.0 | 0.9 | 0.3 |
| Medium | 1.4 | 368 | 4.4 | 3.4 | 1.2 |
| Wealthier | 1.3 | 217 | 3.1 | 2.4 | 0.8 |

[1] Food Self-Sufficiency Ratio = Energy in food produced per capita / Energy needs per capita (in average 3 $GJ\ y^{-1}$)

## 4. Discussion

At all the sites, the poor farm households used much smaller amounts of N *per capita*, had lower cycling indices (indicating that these farms were less integrated), had a less organised network of N flows, and were more dependent on N import to sustain the system activity (TST). Less organisation means that the nutrients are not applied to the compartments that contribute to cycling and productivity of the system. Opportunities for recycling are mainly created by livestock, because without livestock farmers are often not able to collect the equivalent amount of N in materials to mulch their crops or produce compost, because of labour constraints. Without livestock and manure

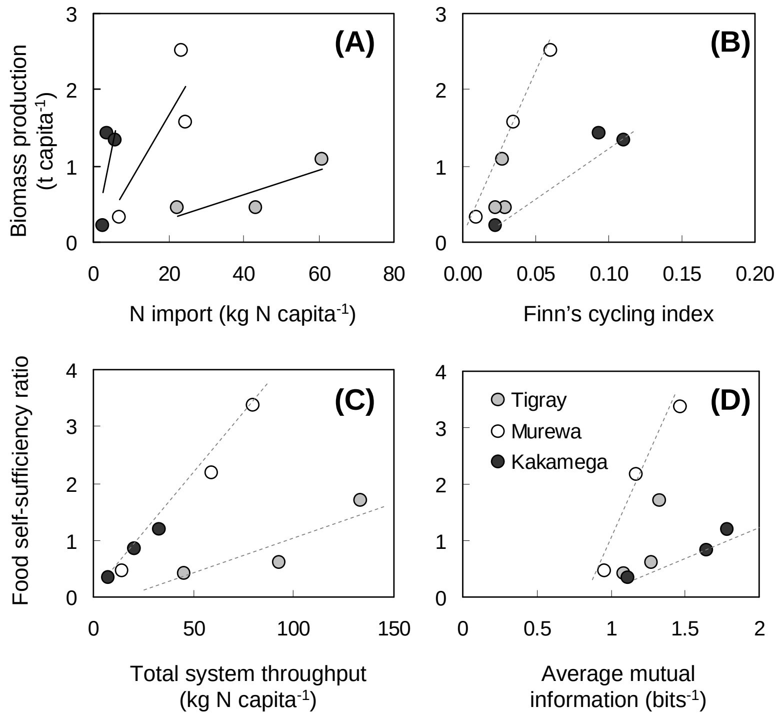



Figure 7: Biomass production plotted against (A) N imports and (B) Finn's cycling index for farm households of different type at three different sites: Tigray (Ethiopia), Murewa (Zimbabwe) and Kakamega (Kenya); and food self-sufficiency, (calculated as the ratio of food produced on farm *per capita* divided by the average energy needs of the farm household member) plotted against (C) Total system throughput (T..) and (D) Average Mutual Information (AMI), for the same farm households. See section 2.1. and Table 1 for details.

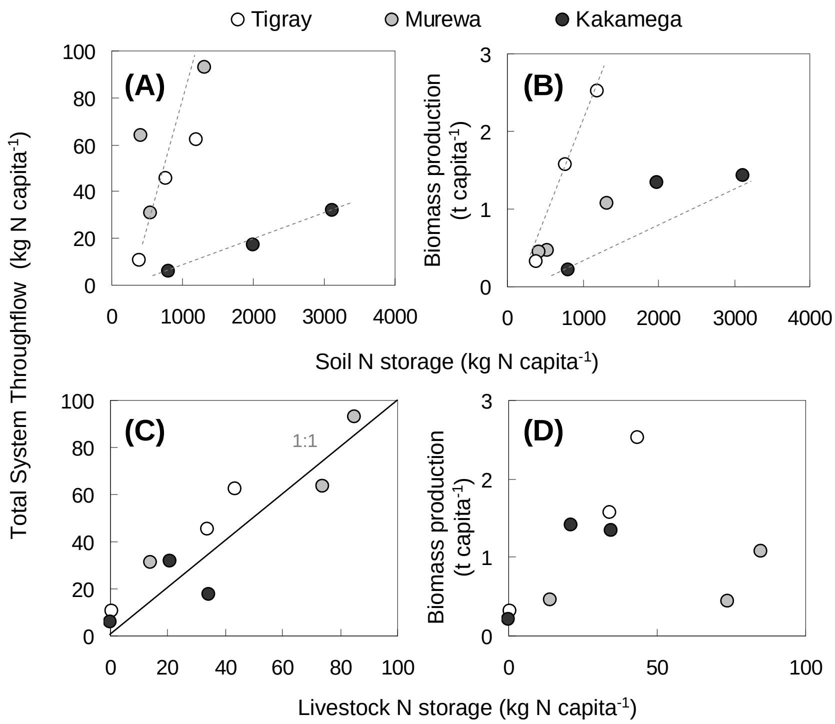



Figure 8: Total system throughflow (TST) plotted against (A) Soil N storage per capita and (C) Livestock storage per capita; Biomass production plotted against (B) Soil N storage per capita, and (D) Livestock storage *per capita*, for farm households of different type at three different sites: Tigray (Ethiopia), Murewa (Zimbabwe) and Kakamega (Kenya).

management, there are few internal flows in the system. Despite these opportunities, recycling was poor for all farms; all the systems recycled less than 25 kg of N per year per farm, and the poor households less than 5 kg of N per year per farm.

Livestock did not contribute much directly with animal products to consumption of the household members, and therefore the large system size (in terms of N flows, T..) is not reflected in a large increases in food self-sufficiency nor in biomass production in Tigray (cf. Fig 7C). Increases in the size of N flows (T..) and N imports led to increases in production and food self-sufficiency in all three sites, although with different conversion efficiencies (cf. Table 5). Inefficiencies may be caused by feeding management, crop residues being removed from the fields, with little or no return in the form of manure N, because manures or crop residues are often applied to other fields (closer to the homestead) than those where cattle feed. The systems with small T.., and little organisation in network of flows (low AMI) were less productive and less food self-sufficient than the systems with large T.. and AMI (cf. Fig. 7C and D). But, at large values of T.. and AMI, food self-sufficiency and productivity were different at each of the sites. Increasing T.. had a relatively smaller effect on food self sufficiency in Tigray than in the other two sites.

The main advantages of having livestock are the provision of draught power for cropping and that they are crucial in moments of crisis when its contribution to food security is the most valued and often realised by selling of animals (Dercon, 2002; Moll, 2005). This means that a farm household uses relatively large amounts of N from the surrounding environment that does not directly contribute to produce food, because the animals fulfil different functions. The high T.. in Tigray was mainly caused by the large size of the N inflows, while the contribution of the organisation of the flows is not as important in this site as in Kakamega. It appears that in Tigray there is more scope to increase the intensity of cycling given the actual diversity of the system.
Higher diversity in flows may be positive if the N flows are organised to increase recycling and there is integration between the system compartments. The impacts of recycling on food self sufficiency thus depends on how the flows are managed, the N conversion efficiency and risks associated in the longer term (i.e., whether the inflows that contribute to the positive feedbacks can be sustained or not). The importance of these factors differs per environment; there will be trade-offs between actual productivity and reliability in the long term.

It appears that increasing the size of network of the N flows will increase food self-sufficiency. Increases in organisation of the flows, and increased recycling may contribute partially to increase in size of the network of flows, but the capacity of the system for recycling is limited by the size of the inflows and of the outflows (marketed products), and from the storage. Cycling reduces dependency on external inputs, and may also increase the efficiency of resource use at the farm scale. The reduced dependency on external inputs, associated with an increase in recycling, supported by larger soil storages in Kakamega, may be indicative of the adaptability of the systems to different stresses (e.g. market failures). The measures of size (T..) and the measure of activity (TST) in contrast, give an estimation of the amount of N that is used to achieve the current production level, and are useful to compare different farm types in terms of performance and efficiencies.

Ecology regards mature ecosystems as characterised by organised patterns of material and energy flows, intense recycling, relatively little dependence from the exterior environment and low productivity (Odum, 1969). Their resilience is sustained on a structure that supports a diversity of flow paths that allows buffering of external shocks and the increased efficiency of few of their flow paths that are not affected by external stressors. Agro-ecosystems have in contrast to fulfil the goals (and aspirations) of the farmers, for which they need to be productive, reliable, (i.e. production should be stable or increase in the longer term) (Conway, 1987), and adaptable to match opportunistic decision making. Finding the balance between these properties is challenging as smallholder crop-livestock systems that are diverse may be more adaptable and can spread risk, but this may lead to apparent resource use inefficiencies.

More organised pattern of flows, and more recycling should lead to less reliance on external input. This is schematically represented in Fig. 9A, where system A is a less productive systems but more reliable. The system productivity is limited by a combination of resources availability and the system configuration. System B, with larger external inputs is more productive, more dependent but may result less reliable because of large fluctuation caused by external (and sometimes internal) stressors such as market collapse, lack of inputs or death of cattle. System A may represent the poor household, and system B the wealthier farm households at each of the sites. The drivers of systems A and B differ at each of the sites, and in these crop-livestock mixed systems are related to the degree of intensification. In Tigray, relatively large inflows from grasslands through livestock, small inflows as fertilisers, and relatively poor internal cycling characterise and sustain the production of system B. These inflows and internal cycling are less important for system A (poorer households) (Fig. 10A). In Kakamega, the inflows into the systems are relatively small, and the production is sustained on internal cycling (included the contribution from the storages) (Fig. 10C).

Murewa represents an intermediate situation where inflows from grasslands, and external agricultural inputs contribute to food production with a relatively small contribution of internal cycling but more important than in Tigray (Fig. 10B).

Agro-ecosystems have to be productive and fulfil their goals, but in risky environments elements that give adaptability and reliability are needed. Cycling and internal organisation, may contribute to those system properties, sometimes at expenses of resource use efficiency as it is the case when inflows to the systems are mediated through livestock due to inevitable losses through cycling. A balance between productivity, adaptability and reliability is needed. Diversity and cycling may contribute to all these properties, but this contribution will depend on the context in which the farmers operate. The lower dependency, high diversity and cycling at Kakamega is associated to relatively better conditions for agricultural production in terms of soil and climate.

The organisation of the system can change to meet different goals: simpler structures may support productive systems, but those may be more vulnerable to (environmental) stress. In agro-ecosystem larger exports may facilitate the acquisition of inputs that may increase productivity, if farmers reinvest in farming. But when this is not the case, large export may feedback negatively in food self-sufficiency and food security. In farming systems, producing export is critical to generation of cash for other needs than food, also to purchase key inputs to production, so it cannot be reduced or eliminated to conserve nutrients. To find a balance between system properties is the challenge,

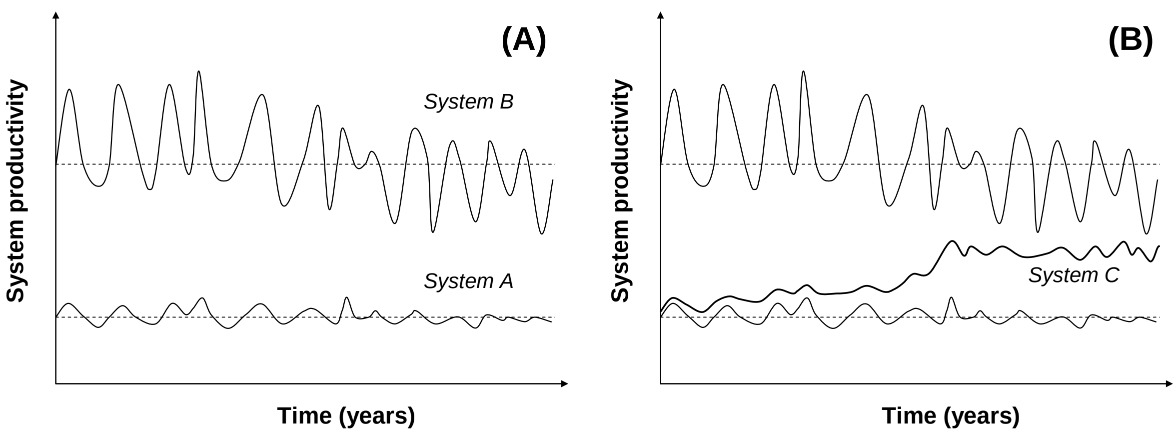



Figure 9: (A) Theoretical representation of the evolution of the productivity of a crop-livestock system. System A represents a less productive but more reliable system than system B which shows large fluctuations caused by external (and sometimes internal) stressors. (B) Theoretical representation of the evolution of the productivity of a crop-livestock farm household system which evolves due to reconfiguration (or system shift) from system A of low productivity into system C finding a balance between productivity and reliability.

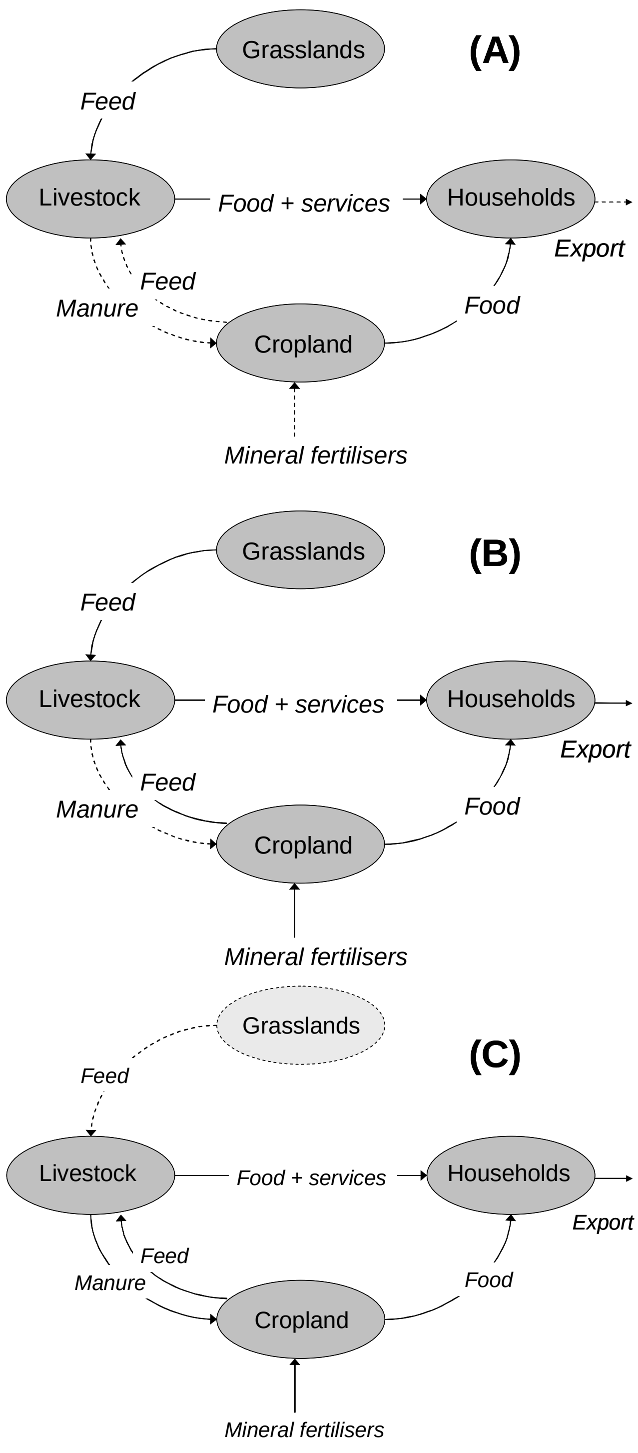



Figure 10: (A) Schematic representation of crop-livestock systems at a relatively low level of intensification, where most feeds come from grasslands, there are weak feedbacks between the cropping and the livestock system, and relatively low agricultural inputs. The main feedbacks among the system compartments are shown where a solid line represents a large flow and a dashed line a small flow. (B) Crop-livestock system at a higher degree of intensification, where grassland and cropland contribute to the feeding of livestock and the imports of agricultural inputs are relatively more important than in A. (C) Crop-livestock system at a high degree of intensification, where most feed is produced in cropland, and where there are strong interactions between cropping and livestock activities.

which most probably will be met by a technical change (or system shift), in which reconfigurations allow to achieve higher productivity without increasing enormously dependency. This is illustrated in Fig. 9B, where the new configuration of system C, approaches the productivity of system A, but is more reliable.

The contribution of diversity and organisation of the network of flows to the system performance should become evident from observation from the same system in a time series. We plan to compare snapshots of more systems from similar regions, and have encountered an unique data sets of farms that have been monitored for a number of years (Ousmane et al., 2008). We believe that Network Analysis can be useful to compare more contrasting systems, such as an African crop livestock system *vs* Swidden systems in Asia, Brazilian soybean monocultures *vs* intensive European farms. These will be the subject of future research. NA can also be used using different currencies, e.g. phosphorus, carbon or energy. Comparing results from such analysis with the N flow analysis will give more insights in the extent towards NA can reflect diversity and integration in farming systems. Modelling techniques can be useful test the effects of increasing cycling or changing system configurations on the system productivity at different scales.

## 5. Concluding remarks

In the crop-livestock systems of the highlands of East and southern Africa we analysed, organisation and diversity of the flows differed more among farm types than across sites. The differences in system performance were explained by both differences in size of the inflows and organisation and cycling. The systems operate in contrasting conditions in terms of agro-ecological potential (rainfall and soils), population density and market accessibility and in the relative importance of livestock in the system. This leads to differences in the types of N inflows (e.g. fertilisers, feed), system diversity and cycling. Comparing indicators of NA indicators with system performance showed that both increases in size (amounts of N that circulate within the network) and organisation of the flows lead to increases in productivity and food self-sufficiency. As these strategies also reduce dependency, combination of both strategies may benefit not only productivity but also adaptability and reliability of smallholders crop-livestock systems.

Chapter 7

# Collective management of feed resources at village scale and the productivity of different farm types in a smallholder community of North East Zimbabwe[†]

[†] This chapter is a summary from:
Rufino, M.C., J. Dury, P. Tittonell, M. T. Van Wijk, M. Herrero, S. Zingore and K.E. Giller., Collective management of feed resources at village scale and the productivity of different farm types in a smallholder community of North East Zimbabwe, Submitted.

## Abstract

Addition of organic materials is needed to sustain the crop productivity of inherently poor soils in the mixed crop-livestock systems of the communal areas of NE Zimbabwe. In these systems, livestock feed resources are collectively managed, with the herds of the village grazing on natural grasslands during the rainy season and on crop residues during the dry season. This creates different types of interactions between the members of the community, cattle owners vs. non-cattle owners, including competition for the organic resources. In this study we explore the magnitude of such interactions in terms of nutrient flows and the long term effects of the current practices on soil productivity, hypothesising that the collective management of feed resources brings negative consequences for non-cattle owners. We used information on crop and cattle management collected in a village of the communal area of Murewa in NE Zimbabwe, and a dynamic farm-scale simulation model (NUANCES-FARMSIM) of which the individual models have been calibrated and tested with existing information for the same area, and adapted to include the main interactions at village scale. The simulations of 10 years showed that the grasslands contributed the majority of the annual feed intake of the herd of the village (c. 75%), and that the crop residues produced by the non-cattle owners sustained a substantial (c. 30%) amount of the intake of cattle during the dry season. This removal of C (0.3−0.4 t C $y^{-1}$) from the fields of the non-cattle owners resulted in a long term reduction of the already poor yields of their farms. Impeding the access of cattle to the crop residues of non-cattle owners increased the quality of their soils modestly and improved yields in the mid- to long term, but not enough to meet the energy needs of the family. Due to poor management of the manure, from the 80−120 kg N left in kraal per year by the cattle owners of wealthier farm type (resource group 1, RG1) and the 40−60 kg N per year for resource group 2 (RG2), only 15−32 and 8−18 kg of N per year were available to be applied to the crops as manure total N for RG1 and RG2 respectively, with an efficiency between N excreted and N available to be applied to the fields of 20−30%. According to the model simulations, the whole herd of the village with average size of 187 animals transferred 100 t faecal dry matter $y^{-1}$ from grasslands to cropland. With minimum losses, that amount will not suffice for 10% of the 116 ha of cropland, if it were to be applied at the recommended rates. Due to the harvest of grain and the removal of most crop residues by grazing cattle, the soil C stocks of all farm types had a negative change at the end of the simulations. The smallest decrease (−0.5 t C $ha^{-1}$ in 10 years) was observed in the best fields of the cattle owners who compensate for the removal of C through the addition of manure. To sustain the herd size, cattle of the farmers from RG1 (in average 10 heads) consumed between 20−25 t of grass biomass $y^{-1}$. Without taking into account the negative effect of overgrazing on the pastures, each farmer of RG1 would need to have access to 12−27 ha of grassland to apply about 3−4 t of manure $y^{-1}$ in their farms with an average size of 3 ha. Adding inputs to the whole (community) system in the form of mineral fertiliser concurrently with changes to the current management of the crop residues and manures by redistributing manure from the more fertile fields of the farm to the poorer soils, appears to be a promising strategy to boost the productivity of the community as a whole. The likelihood of this scenario being implemented depends on the availability of fertilisers and the willingness of farmers to invest in rehabilitating soils to obtain benefits in the long term, as opposed to concentrating all organic inputs in small areas and creating islands of fertility where crop yields are secured.

**Keywords:** Sub-Saharan Africa, maize-based system, cattle, crop-livestock integration, modelling, Miombo woodland

# 1. Introduction

The dominant type of farming system in the communal areas of north-east Zimbabwe is crop-livestock mixed (Kunjeku et al., 1998). The main interactions between the crop and livestock are through the use of draught power for ploughing the land, the animal manure which is applied to the crops, and the use of crop residues as feed for livestock (Steinfeld, 1988). Manure is needed to sustain crop production because soils are inherently poor sands and mineral fertilisers (N, P, K) alone are insufficient to achieve the crop yields required to meet the family food requirements (Rodel and Hopley, 1973; Grant, 1976). Cattle are the dominant livestock kept by farmers. Smallholder farms are heterogeneous in terms of land area available and numbers of cattle, with only 40% of the households owning cattle (Zingore et al., 2007b). Rainfall variability represents one of the largest risks to farming in NE Zimbabwe, where the frequency of occurrence of droughts has increased in last twenty years (Matarira et al., 2004), and may increase further due to the effects of climate change. Droughts have a clear short term effect on food and grass production, exposing everybody within a community to risk.

Within the communal area of Murewa, each village has access to well-delimited communal grasslands where cattle are herded during the growing season to avoid crop damage. This is the period in which the feed quality of the grasses is relatively good. During the dry season, shortly after the crops are harvested, cattle graze freely within the village cropland. Cattle graze preferentially maize and groundnut residues available in the croplands. Many cattle owners remove their crop residues to feed the cattle later in the dry season, when feed shortages are more critical (Powell and Williams, 1993; Mtambanengwe and Mapfumo, 2005). The harvesting of residues from cropland is a common practice in communal areas of Zimbabwe (Mtambanengwe and Mapfumo, 2005), that may have negative consequences for crop production because of the continuous removal of carbon (C) from the fields, especially for farmers who have no access to animal manure. However, no quantitative information is available on the complex interactions between cattle grazing both in grasslands and croplands, and the nutrient and organic matter flows associated with these interactions.

The collective management of the herds of the village, and the tolerance of the farmers without cattle to the grazing of their crop residues contributes to the concentration of C and nutrients in the fields of the cattle owners. While the intensity of such interactions regulates the degree of inequity between farmers, rainfall variability has a large effect on the intensity of these interactions. The goals of this study were to assess the magnitude of such interactions at the community level and to explore their impact on the long-term productivity of different farm types, i.e. cattle farmers *vs* non-cattle farmers. Focus was placed on the interactions mediated by collective management of feed resources, under current and alternative management practices. To achieve this, we combined information available for the area of study, collected through interviews, observations, experiments, and literature. We used the NUANCES-FARMSIM modelling framework (Giller et al., 2006) (see www.africanuances.nl), which consists of relatively simple crop, cattle, organic resources management and grassland models, that have been adapted and tested for the conditions of smallholder farming in Murewa, NE Zimbabwe. A number of scenarios were imposed to explore the benefits of management strategies for different farm types under current and alternative practices.

The specific research questions were:
(i) What is the magnitude of the flows of C and nutrients mediated by cattle at both the farm and community scale? How variable are these flows in time? How do they change according to different management practices (scenarios)? (ii) How large are the flows of C and nutrients from grasslands to croplands, and the redistribution of C within the cropland from fields of non-cattle owners to fields of cattle owners? (iii) What is the effect of rainfall variability on these interactions? When do the critical risky moments occur in terms of competition for organic resources?.

# 2. Materials and methods

This analysis was built on detailed information that describes the resources, the farms, the soils, and the cattle of a smallholder village in Murewa, NE Zimbabwe. For the explorations, a descriptive and dynamic modelling approach was chosen. The analysis tool, a model that simulates the dynamics of the production of the cropland and the grassland, was adapted and calibrated for this work. In this section, we introduce the area of study, the analysis tool with the main simplifications and assumptions, and elaborate a number of management scenarios that are used for exploring the impacts of management choices on resource flows.

## 2.1 The study area

The site selected for this study is in the Murewa smallholder area located 80 km E of Harare in Zimbabwe and lies between 17 and 18°S and 31 and 32°E. The area is situated in Natural region II (Vincent and Thomas, 1960), an agro-ecological zone of relatively high potential for agriculture. The main crop in Murewa is maize, with groundnuts, sweet potatoes, sunflower and vegetables also present. Cattle are the main livestock usually grazing in common grasslands during the day and tethered in the kraal close to the homesteads during the night. Crop residues are fed to cattle during the dry season and manure is used to fertilise maize crops and vegetable gardens.

### *2.1.1 Climate, soils and natural vegetation*

The Murewa area has a sub-tropical climate and it receives 750−1000 mm rainfall annually, distributed in a unimodal pattern (November−April), with an annual coefficient of variation of 30% (Kunjeku et al., 1998). The soils in the area are predominantly granitic sandy soils (Lixisols) with low inherent fertility (Nyamapfene, 1991). A smaller proportion of the area has more fertile dolerite-derived clay soils (Luvisols) that are considered the best agricultural soils in Zimbabwe. The natural vegetation at Murewa is Miombo woodland dominated by *Brachystegia* spp. and *Julbernardia* spp. trees. The grass cover in the woodland is dominated by species of the genus *Hyparrhenia*, and therefore receives the name of Hyparrhenia-veld type (Rattray, 1957). *Andropogon*, *Digitaria*, and *Heteropogon* spp. are also common species especially where the tree density is higher. Where grazing intensity is relatively high, and in the wetter 'vlei' area, *Sporobolus pyramidalis* dominates the grass strata.

### *2.1.2 The farmers and the typology*

A common approach when modelling agro-pastoral communities is to stratify farm households using simplified typologies (Thornton et al., 2003; Thornton et al., 2007). We constructed for this study a simplified 'virtual' village that resembles the Majonjo village located in Murewa. We used the farm typology developed by Zingore et al. (2007b) which distinguishes four farmer resource groups (RG) based on cattle ownership, farm size, production orientation, hiring labour, and food self-sufficiency (Table 1). For these farm types, information on field sizes, soil quality, input use, and crop yields was available. Feeding strategies, herding patterns, crop residues, and manure management were studied during the dry season of 2006 and the rainy season of 2007 (Dury, 2007). This second characterisation focused on cattle and cattle management in the village, in which cattle owners, crop farmers and other key informants (e.g. the kraal head, herders) were interviewed. Additionally, the communal grasslands were characterised in terms of biomass production and species composition both during the rainy and dry season (Dury, 2007).

Table 1: Characteristics of the different farm types classified according to the farm typology result of group discussions with farmers from a village from the communal area of Murewa. Source: Zingore et al. (2007b).

| | Farm type | | | |
|---|---|---|---|---|
| | Wealthier | Medium-wealthier | Medium-poor | Poor |
| Resource group | RG1 | RG2 | RG3 | RG4 |
| Proportion in the village (%) | 6 | 35 | 26 | 33 |
| Livestock owned | c. 10 cattle | < 10 cattle | No cattle | No cattle |
| Resource exchanges | Hire labour and shares draught power | Do not sell or hire labour, shares draught power | Sometimes sell labour or exchange it for draught power | Sell labour and /or exchange labour for draught power |
| Land holding (ha) | > 3 | 2- 3 | < 2 | < 1 |
| Food self-sufficiency | Self-sufficient Able to sell grain and vegetables | Self-sufficient Able to sell grain and vegetables | Purchase grain and sell vegetables | Need to purchase food or receive food aid |

## 2.2 The modelling framework

### *2.2.1 Farm-scale model*

NUANCES-FARMSIM is a farm-scale decision making model, where household objectives, constraints and resource allocation patterns are simulated, linking the simulation results from different sub-models. Crop and soil modules are combined at field scale in the model FIELD (Field-scale resource Interactions, use Efficiencies and Long-term soil fertility Development – Tittonell et al. (2007)). Different combinations of crop types and soil properties can be simulated for different field types (e.g. infields and outfields). LIVSIM (LIVestock SIMulator–Rufino et al. (2007a) – Appendix 1) is a model that simulates animal production based on feed quality and availability. The dynamics of nutrients through manure collection, storage and use are simulated by HEAPSIM (Rufino et al., 2007b) in which a fuzzy-logic approach is used to estimate mass and nutrient transfer efficiencies through manure collection and storage. The variability in weather and the inflow of cash or kind from off-farm sources constitute inputs to FARMSIM that are accounted for and/or modified for scenario simulation. Experimental data and, when possible, calibrated process-based models are used to generate functional relationships that are built into the various sub-models of FARMSIM. The sub-models incorporate processes and interactions in a descriptive fashion, and operate with different time steps: monthly for cattle, and the manure management, and seasonal for annual crops. A detailed description of the various components of the farm-scale model, and a sensitivity analysis can be found in Van Wijk et al. (2008).

*FIELD, the crop model*

FIELD simulates long-term changes in soil fertility (C, N, P and K), interactions between nutrients that determine crop production, and crop responses to mineral fertilizer and/or manure applications. Resource-limited total dry matter and grain production are calculated in FIELD on the basis of seasonal resource (light, water and nutrients) availabilities through application of crop specific resource use efficiencies for capture and conversion, derived from literature, experiments and/or process-based modelling work. The simulation of soil processes and the calibration and testing for the study site are described by Tittonell et al. (2007).

*LIVSIM, the livestock model*

LIVSIM simulates the performance of individual animals in time according to their genetic potential and feeding. Potential production is defined by mature weight, growth rate and milk yield. The basic structure is based on the model developed by Konandreas and Anderson (1982). LIVSIM differs from that model in that: (i) the nutritive requirements calculations are based on AFRC (1993), (ii) feed intake is based on the model of Conrad (1966), (iii) excreta production, and (iv) the decision rules. The calibration and testing of the model can be found in Rufino et al. (2007a). For this study, LIVSIM was complemented with a grazing routine that includes diet selection and restrictions to feed intake. The approach includes functional relationships between intake and herbage mass, grazing behaviour observations, where we sought a good balance between flexibility *vs* simplicity to be able to deal with diverse diets. The influence of the spatial distribution of feed on the diet selection was treated in LIVSIM at different levels based on the concept developed by Senft et al. (1987) in their hierarchical foraging model by taking into account herding strategies. The main advantage of this approach is its simplicity and that considers management (Senft, 1989), assuming that herders choose the land units for grazing. This is captured by using the relative time spent at each grazing unit, which is input to LIVSIM. Selection is accounted for by using a preference index based on crude protein and abundance of the main grass species. Potential intake was adjusted with a relative intake coefficient to describe actual dry matter intake (Johnson and Parsons, 1985; Richardson et al., 1991) to take into account the constraints imposed by herbage availability (Herrero et al., 1998). Feed allocation among animals of the same herd is based on the relative energy requirement for each individual animal. Dejections during the day were proportional to the time spent at each grazing unit. More details on the grazing routine can be found in the Appendix 1 in Section 3.1.

*HEAPSIM, the organic resources management model*

We adapted HEAPSIM as described in Rufino et al. (2007b) to represent the description of the manure management for the Manjonjo village. The manure excreted during kraaling is left to accumulate until August mixed with the maize stover added by farmers and not consumed by cattle. In August manure is heaped in the open air with no protection against rain and harvested for application during planting time in November. In the village 35 farmers (cattle owners) were interviewed on their manure management practices. Most farmers (85%) removed the manure from the kraal once a year. Only 20% of the farmers did not compost the manure collected from the kraal and applied directly to the fields. Most farmers said to apply the manure (between 1.8−7.2 tonnes $ha^{-1}y^{-1}$) to the maize fields between October and November. The compost consisted of manure mixed with feed refusals heaped and left to decompose for 3 months on average during the dry season, usually between August and October. About 30% of the farmers removed variable amounts of manure from the kraal to be applied in the vegetable garden during April−July or in November.

*2.2.2 Village scale model*

Different instances of FARMSIM were used to simulate the different farm types of the village (Fig. 1). A new model, GrassSIM (Grass SIMulator) was developed to simulate grass growth as a function of rainfall use efficiency, grazing pressure, and soil quality. This model described the availability of green and dead grass from the different grassland units. The herd, simulated by LIVSIM, grazed on the grassland during the day, and was kept overnight within a kraal on the farm, where manure accumulated. The dynamics of manure decomposition before the collection and during the composting period was followed by HEAPSIM for each farm type. Different instances of FIELD were used to simulate aboveground biomass and grain production, and soil C in the different field types of each farm type. During the dry season cattle was allowed to graze the crop residues of the farm types that granted access to them, and the manure produced during that period was left in the grazed field, and incorporated (after C and nutrient losses) into the soil module of FIELD.

*2.2.4 Grassland model – Grass-SIM*

This model describes dynamically the production of grass and dead biomass for land-scape units of different soil quality and grazing pressure, as a function of rainfall use efficiency (RUE). This approach has been used with success in semi-arid rangelands in the past (Le Houérou, 1984; Le Houérou et al., 1988; Illius and O'Connor, 1999). Our model is based on the concepts used in model developed by Gambiza et al. (2000) for simulating the production of Miombo woodlands in Southern Africa. Rainfall use efficiencies ranged from 1.7 to 3 kg DM per mm rain for soils with low (0.8%) to high (2.1%) SOC, and stocking densities from 0 to 1 Livestock Unit ha$^{-1}$. The rainfall use efficiencies were calculated from data available for the grass strata of similar Miombo woodlands (Barnes, 1956; Baars, 1996; Frost, 1996) and agree with observations of Illius and O'Connor (1999). Data collected by Dury (2007) was used to calibrate grass at peak biomass, senescence and decay for the different grazing units. An example of simulated grass for the different landscape units defined in the village together with more detail on the data collection can be found in Appendix 2 and 3.

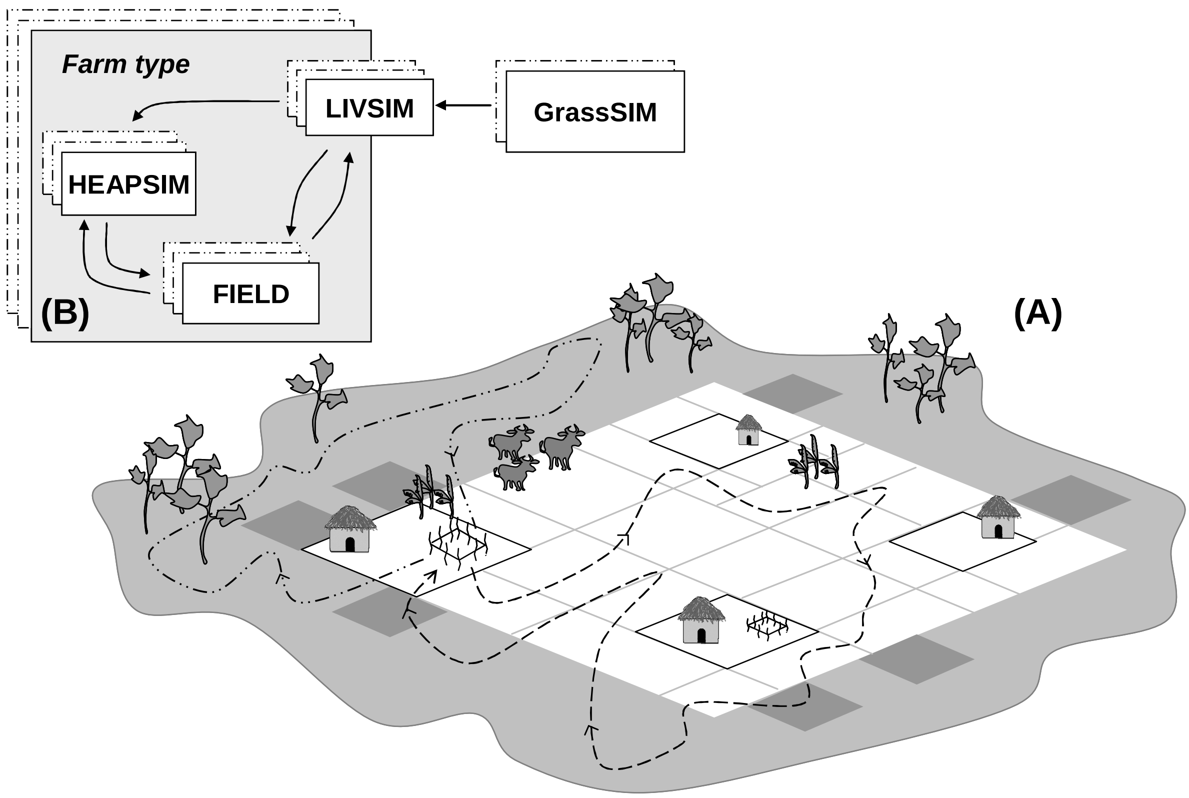



Figure 1: (A) Schematic representation of the virtual village and of the integrated model used for this study. The village consists of land allocated to cropland surrounded by land allocated to grazing. Different farm types or resource groups were defined on the basis of their resources: land, livestock heads, labour availability. (B) The model FARMSIM has been adapted to take into account the interactions between different farm types due to livestock feeding management. FIELD simulates crop production and the dynamics of C and nutrients in the soils, LIVSIM simulates animal production and reproduction of the herd, HEAPSIM describes decomposition of manures and organic resources in the kraal and in the compost heap, GrassSIM describes the availability of green and dead grass in the different grazing units. The different models are linked dynamically and management is described by using rules derived from interviews and observation in the area of study.

## 2.3 Simplified farm types, model inputs, parameters and assumptions

### *2.3.1 The village and the farmers*

The simplified village consisted of 66 households, from which 4 farmers (6%) belong to RG1, 23 (35%) to RG2, 17 (26%) to RG3 and 22 (33%) to RG4 (Table 2). The land consists of 116 ha of cropland and 426 ha of communal grassland and woodland (Fig. 2), of which a large unit of about 160 ha is hardly used for herding because it is difficult to access. In this village, availability of forage during the growing season is not limiting cattle production, calculated stocking rate were 0.3 and 0.5 LU (Livestock Units) per hectare, for the rainy and dry season respectively. From the original village of Manjonjo, we excluded the households and the smaller cropland close to the Nyagambe river, located at the eastern side of the hill (Fig. 2), because the two sectors of the original village do not share feeding resources during rainy season, or during the dry season. The total area under cropping remains constant, and the proportion of farm types in the village does not change, i.e. non-cattle farmers do not evolve into cattle farmers within the simulation time, although the opposite may happen if the cattle die due to diseases or starvation. In reality, farm households are not static, and poorer households may gain resources and *vice versa*, but as the main goal of this study was to examine community trade-offs and what is feasible within the boundaries of the resources available to the village, such an assumption is justifiable.

### *2.3.2 The herd dynamics and herding patterns*

The cattle farmers share the responsibility of herding the cattle from the whole village during the growing season. During the dry season cattle is not herded and allowed to roam around the village cropland consuming the crop residues available. At the beginning of the simulations the herd consisted of: 155 heads, 58% from the local Mashona breed and 42% Africander, 26% of the cattle belonged to the RG1 farmers and the rest to RG2 farmers. The initial composition of the herd was similar to that observed in the village, with 30% cows (calved at least once), 17% heifers, 14% steers (males younger than three years), 25% adult males (including oxen and few bulls), and 15% calves (younger than one year old) (Dury, 2007). It was assumed that the herding pattern, the routes and grazing units visited during the growing season, described by the herders of the village does not change during the 10 y simulation time. Mortality rates were set to those observed in the same area by French et al. (2001). Offtake rates of live animals were assumed to be 3% $y^{-1}$ (Hargreaves et al., 2004), animals were removed from all classes, and recruitment into the herd was assumed to be nil. These estimates of herd population dynamics are in agreement with those of Steinfeld (1988) and Chinembiri (1999).

### 2.4 Scenarios

In Figure 3, we show a series of 62 years of rainfall measured at Murewa, in which 25 years were below the average of 800 mm, and 7 years were below 600 mm. From this series we selected three consecutive series of 10 years for the simulations, to include the large rainfall variability of the region. The series 1954−1964 was on average wetter and less variable (mean 900 mm, CV =25%) than the series 1944−1955 (mean 860 mm, CV=30%) that was used for the initial explorations presented in Sections 3.1 and 3.2, while the series from 1965 to 1974 was relatively drier (mean 780 mm, CV =35%).

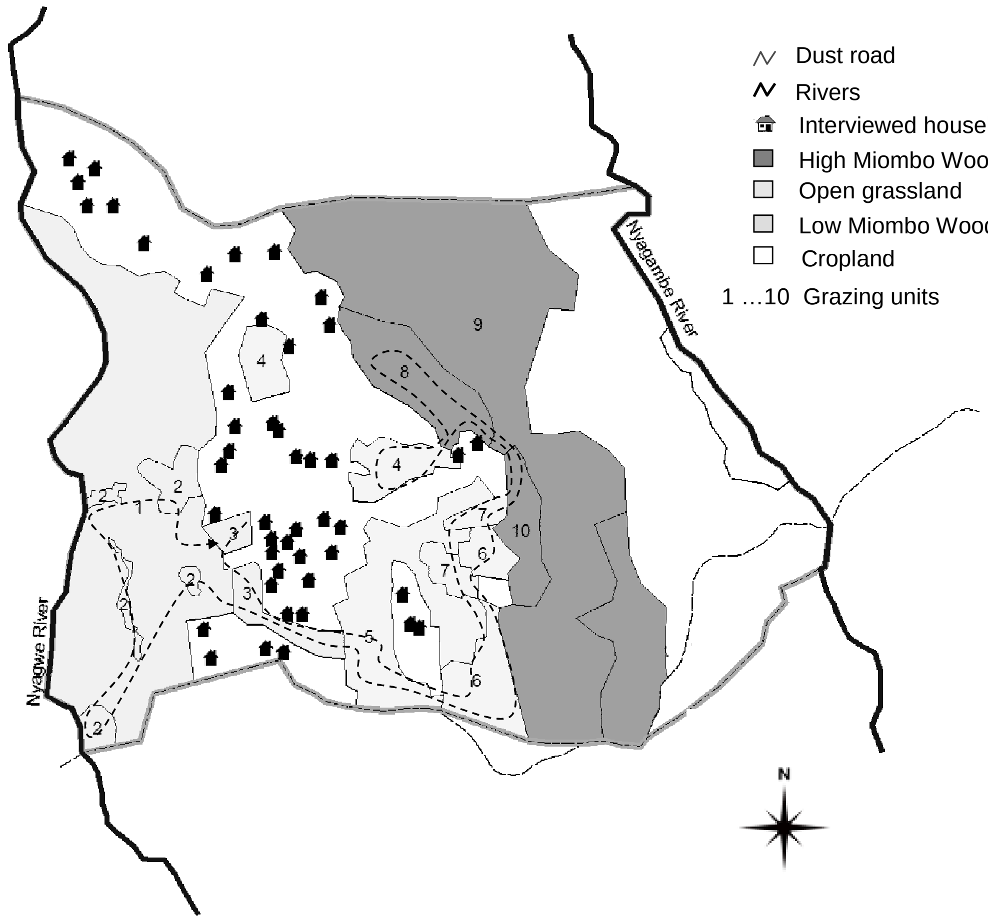



Figure 2: Map of the village used as basis for this study. The village territory is delimited by two rivers and two other village boundaries. The village territory is divided by a hill that extends from N to S, which is covered with high Miombo woodland vegetation (grazing units 8, 9 and 10). The cropland is located between two blocks of grazing land that correspond to the left to the low Miombo woodland landscape unit, and to the right to the open grassland and high Miombo woodland. The houses show the location of the different households.

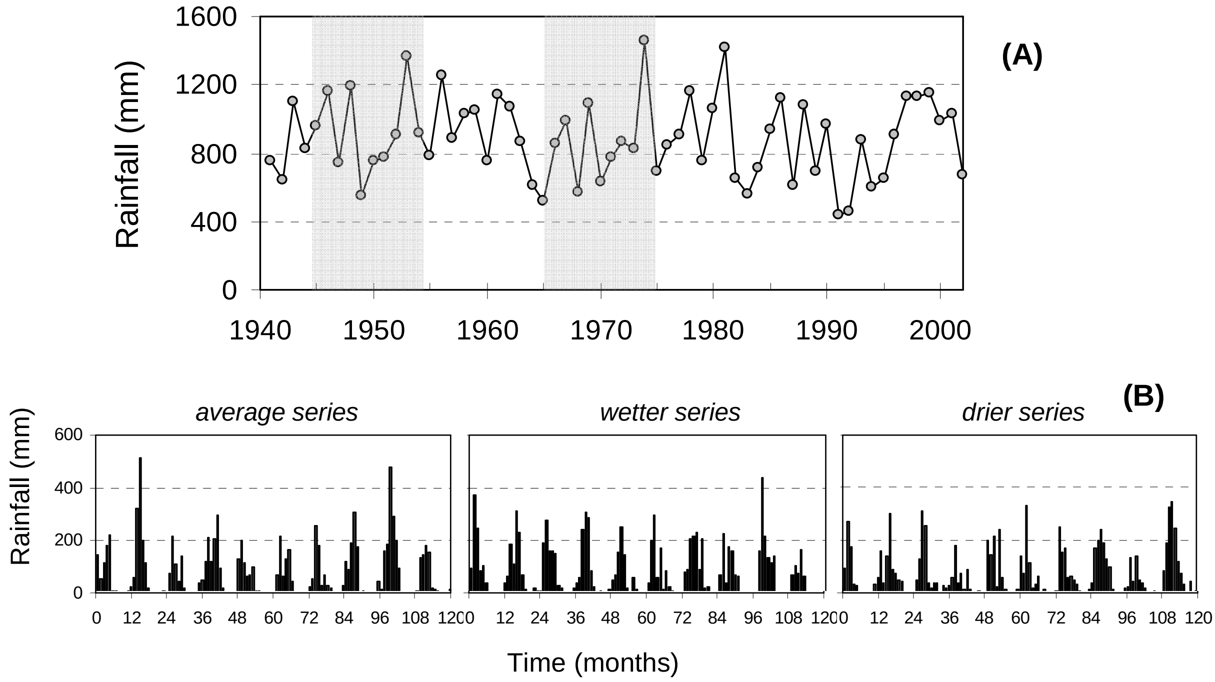



Figure 3: (A) Annual average rainfall for a 60 year period from 1942 to 2002, average 885 mm with CV=27%, (B) Monthly rainfall for three different series of 10 years. The first set from 1945−1954 represents an 'average series', the second set from 1955−1964 represent a 'wetter series' and the last from 1965−1974 a 'drier series'. Each of the rainfall series start in November and ends in October, the annual rainfall shown in (A) is the annual average from January to December which differs slightly from the rainfall presented in (B).

### *2.4.1 Baseline*

This scenario represents current farmers' practices, as described earlier, taking place on simplified farm types (cf. Section 2.3). Farmers from different resource groups remove different amounts of crop residues from their fields, and all allow cattle to graze the remaining crop residue. The RG1 and the RG2 farmers remove 20% of the crop residues from their homefields and use it as bedding for the cattle, and the RG3 and RG4 10%. Fertilisers are applied at higher rates on the home fields and lower rates on the outfields. RG1 farmers used more fertiliser than for the others (Table 2). Farmers from RG1 and RG2 applied manure to their homefields and to their vegetable gardens. We assumed that the manure management was the same for all farms from both RG1 and RG2. Manure is allowed to accumulate in the kraal, sometimes mixed with crop residues used as bedding, and becomes mixed with sand due to trampling by the animals. The manure from the kraal is removed once a year in the dry season and is heaped and composted for a period of 3 months, and applied to the crops.

Table 2: Average farm characteristics and input use and of the different farm types in the virtual village for the baseline scenario (information from Zingore et al. 2007a, b) and input rates used for the targeted fertilisation scenario. For details see Section 2.4.

| | Farm type | | | |
|---|---|---|---|---|
| | RG1 | RG2 | RG3 | RG4 |
| Household size (#) | 7 | 5 | 6 | 4 |
| Farm size (ha) | 3.5 | 2.2 | 1.9 | 0.9 |
| Home field area (ha) | 0.8 | 0.6 | 0.4 | 0.4 |
| Mid field area (ha) | 0.8 | 0.4 | 0.6 | 0 |
| Outfield area (ha) | 1.7 | 1.0 | 0.7 | 0.4 |
| Vegetable garden (ha) | 0.2 | 0.2 | 0.2 | 0.1 |
| Cattle heads (#) | 10 | 5 | 0 | 0 |
| *Input use in baseline scenario* | | | | |
| Fertiliser N (kg N farm$^{-1}$) | 100 | 45 | 35 | 13 |
| homefields (kg N ha$^{-1}$) | 45 | 45 | 50 | 24 |
| outfields (kg N ha$^{-1}$) | 30 | 13 | 5 | 15 |
| Fertiliser P (kg P farm$^{-1}$) | 17 | 10 | 4 | 2 |
| homefields (kg P ha$^{-1}$) | 10 | 10 | 5 | 6 |
| outfields (kg P ha$^{-1}$) | 4 | 2 | 1 | 0 |
| Manure applied (t farm$^{-1}$) | 3−4 | 1.5−2 | 0 | 0 |
| *Input use in targeted fertilisation scenario* | | | | |
| Fertiliser N (kg N farm$^{-1}$) | 174 | 102 | 102 | 48 |
| homefields (kg N ha$^{-1}$) | 30 | 30 | 60 | 60 |
| outfields (kg N ha$^{-1}$) | 60 | 60 | 60 | 60 |
| Fertiliser P (kg P farm$^{-1}$) | 87 | 51 | 51 | 24 |
| homefields (kg P ha$^{-1}$) | 15 | 15 | 30 | 30 |
| outfields (kg P ha$^{-1}$) | 30 | 30 | 30 | 30 |
| Manure applied (t farm$^{-1}$) | 3.5−5 | 1.8−2 | 0 | 0 |

### *2.4.2 The effect of different crop residue management*

In this scenario, non-cattle owners incorporate their crop residues into the soils. We explore the effects of this practice on crop yields for both non-cattle owners (RG3 and RG4) and cattle owners (RG1 and RG2) and animal productivity (herd dynamics, bodyweight changes). Winter ploughing is a tillage practice by which crop residues are ploughed into the soil after harvest around May when the soils are still moist. Cattle would have less feed available during the dry season and this may have an impact on cattle productivity and manure production.

### *2.4.3 Supplementation with fodder legumes*

We explored the effect of supplementing calves and lactating cows with fodder legumes during the dry season, on the herd dynamics, animal productivity, and manure production. Chakeredza et al. (2007) proposed the use of fodder legumes trees to be used to supplement the poor quality roughage (crop residues and grass hay) during the dry season in smallholder areas of Southern Africa. Dzowela et al. (1997), identified that *Acacia agustissima* and *Leucaena* spp. have potential to be used as hay during the dry season. These legumes trees can be planted as hedges on contour-bunds so that they do not occupy crop land, and they can be harvested at regular intervals (6−12 weeks) during the rainy season, and conserved as hay. This fodder technology produces roughly 0.8 t DM $ha^{-1}$, which could supplement 3 animals at 3 kg $d^{-1}$ during the critical period (August-October). Calves were supplemented with 1 kg dry matter per day of legume hay and lactating cows with 2 kg $d^{-1}$ during the dry season from August to October as proposed by Dzowela et al. (1997). Feed quality of the legumes and the quantities supplemented were taken from Hove et al. (2003) and Abdulrazak et al. (1997) and are presented in the Appendix 3.

*2.4.4 Targeted fertilisation*

In this scenario, we explored the effect of increasing fertiliser use in all farm types in line with ideas Abuja declaration of the African heads of state under NEPAD (see www.africafertilizersummit.org). Because of the limited availability of manure for each farm, in the targeted fertilisation scenario we distributed the available manure at a low rate only in the mid and outfields of the farms of the cattle farmers RG1 and RG2. This followed the suggestions of Mtambanengwe and Mapfumo (2005) that organic nutrient resources can be use most efficiently by reducing the amounts applied in homefields, so that they can be spread equitably throughout the farm to facilitate rehabilitation of degraded outfields. Model-assisted explorations by Tittonell et al. (2008b) support the idea that the more fertile homefields can be managed with maintenance fertilisation and conserving crop residues, while mid and outfields need more fertiliser to stimulate biomass production. The fertiliser application rates of 60 kg N $ha^{-1}$ and 30 kg P $ha^{-1}$ used in the simulations were the most efficient rates derived from the experimental work of Zingore et al. (2007a) in the study area (Table 2). In the relatively poorer homefields of the RG3 and RG4, the crop residues were kept and fertilisers were added to all field types. Crop residues from mid and outfields of all farm types were assumed to have been grazed.

**2.5 Model simulations**

To deal with the stochastic elements included in LIVSIM, i.e. conception and mortality, 100 replicate runs were used for each of the scenarios. We compared the outcomes of 100 *vs* 200 replicates, and these were not significantly ($P$>0.05) different.

The length of the simulations was set to 10 years in order to capture effects of the scenarios on soil processes.

# 3. Results and discussion

### 3.1 The magnitude and dynamics of the nutrient flows at village and farm scale

The simulations of the baseline scenario showed a clear seasonal pattern in feed intake and excreta production by the herd of the village. The grasslands contributed the majority of the annual feed intake of the herd of the village, amounting to 75% for the baseline scenario. Grazing of crop residues filled a critical feed shortage during the dry season, mainly because of the low quality of the grass available at that time (Fig. 4A).

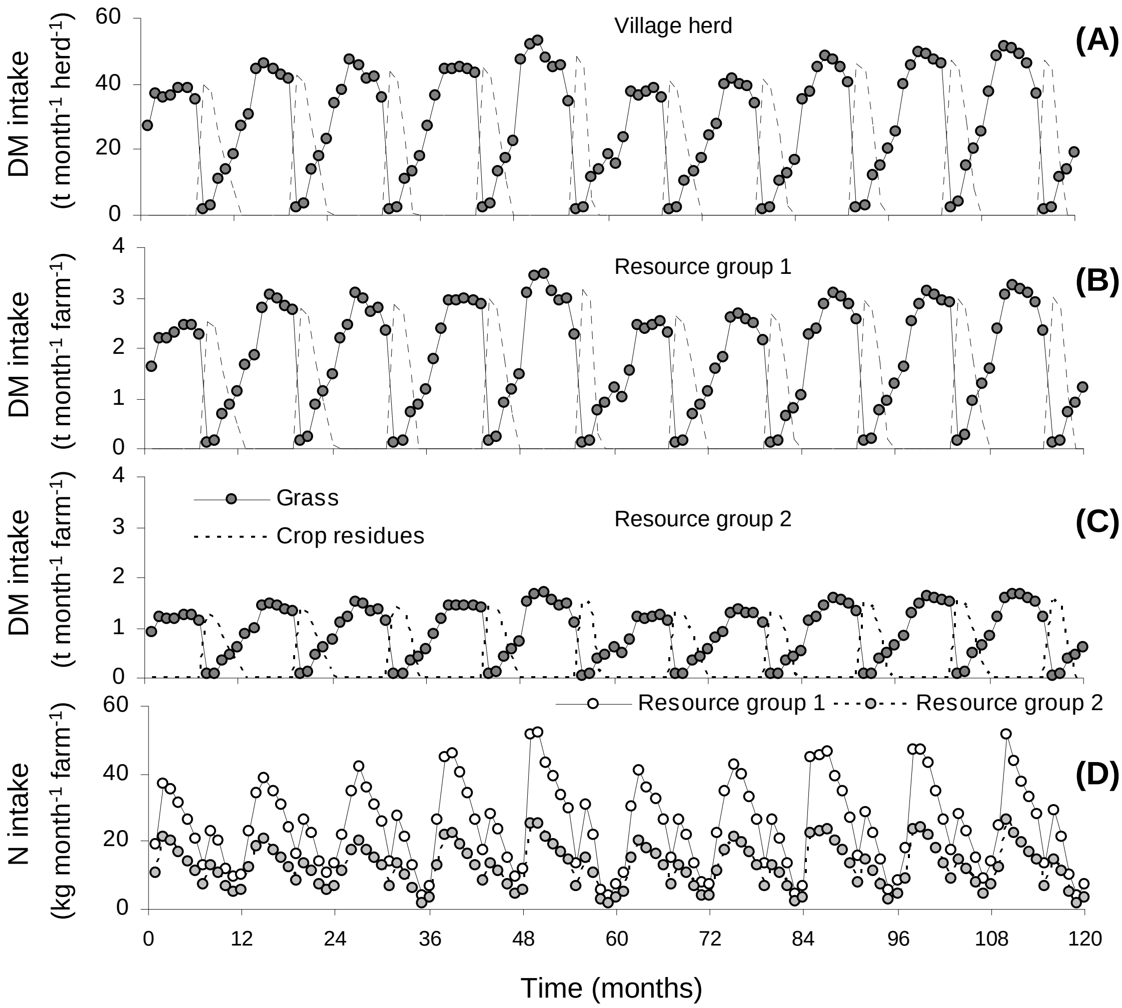



Figure 4: (A) Simulated development of monthly feed intake of dry matter for the whole herd of the village, (B) Dry matter for the herd of a cattle farmer from Resource Group 1 (RG1), (C) Dry matter intake and (D) N intake for the herd of a cattle farmer from Resource Group 2 (RG2) in the 10 year baseline simulation using the ‘average’ rainfall series.

The sharp switch from feeding grass to feeding crop residues observed is due to the (rule based) harvesting of the crops in the simulations, as the farmers cease to herd the cattle once crops are harvested and the headman has declared cattle can be released. Once cattle are allowed to graze the crop residues they remain exclusively in the crop fields until the residues are largely used up as the crop residues are of better quality than the grass. The cattle of farmers of resource group 1 (RG1), consumed twice as much grass and crop residues per farm as the cattle of farmers of RG2 (Fig. 4B and C). At the village scale, the cattle of the RG1 farmers, who each had about 10 cattle, consumed only about 26% of all the feed consumed by the herd throughout the rainy and dry season. Although each of the of RG2 famers owned less head of cattle (about 5 on average), due to the greater number of RG2 farmers they collectively owned the largest part of the herd of the village. The N intake of the herd followed the seasonality in crude protein contained in the feeds, with a peak during the rainy season around January when the forage intake and its quality is highest, while the peak of the dry season, is observed around June when crop residues become available after the harvest of the crops (Fig. 4D). The depressed intake due to low quality of the grass is known for Hyparrhenia-veld type of vegetation, and supplementation with richer protein sources has been advised since the early 60’s (Smith, 1961; Smith, 1962; Clatworthy et al., 1986), but the adoption of fodder legumes or the use of other supplements has been largely unsuccessful in the communal areas of Zimbabwe (Dzowela et al., 1997).

The dynamics of production of manure followed the pattern of the feed intake (Fig. 5A), and the deposition of manure in cropland, grassland and accumulation in the kraal were determined by feeding strategies and manure management. A small proportion of the excreted faecal dry matter was left in the cropland by the cattle through direct dejections during the grazing of the crop residues. Because cattle spent more than half of the time in the kraal (12−14 hours per day according to our observations in the village), the amount of manure that was available for recycling on the farms of the cattle owners was larger than the amount excreted during grazing in the grassland and cropland. The amount of recyclable manure depends on the number of cattle, and therefore each RG1 farmer may recycle about twice as much manure on their farm as each of the RG2 farmers (Fig. 5B). The amount of N contained in the excreta left during kraaling also followed the seasonal pattern of N intake (Fig. 5C), but due to poor management of the manure, from the 80−120 kg N left in kraal $y^{-1}$ by the cattle of RG1 farmers and the 40−60 kg N $y^{-1}$ for RG2, only 15−32 and 8−18 kg N $y^{-1}$ were available to be applied to the crops as manure total N for RG1 and RG2 respectively, with an efficiency between N excreted and N available to be applied to the fields of 20−30%. Manure accumulated in the kraal was on average 7.3 and 3.8 t dry matter $y^{-1}$

before losses, and after composting 2.8 and 1.5 t dry matter $y^{-1}$ and for RG1 and RG2 farmers, respectively. The efficiency of N retention during collection and composting was on average 35−38%. Overall losses of C and N during composting were on average 20−25% because the manure used for composting had already been exposed to large losses during the accumulation period in the kraal (Fig. 5D). At the village scale, about 24% of the cropland was actively manured by farmers just before the cropping season. Large differences in farm-scale crop production were observed between the cattle owners of RG1 and RG2 and the non-cattle owners (RG3 and RG4) (Fig. 6A). These were due to differences in size of the cropped land, soil quality and input use (Tables 2 and 3).

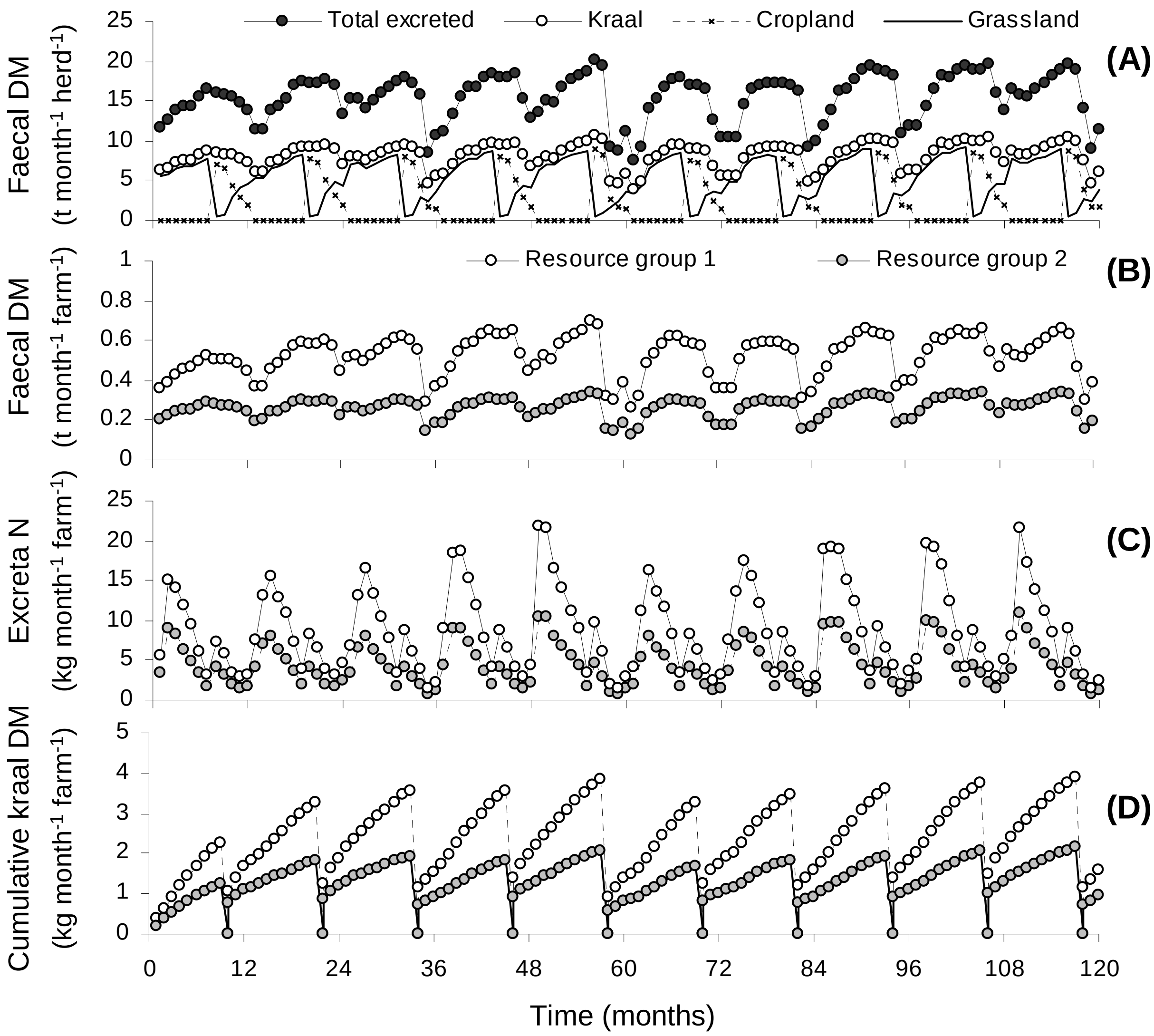



Figure 5: (A) Simulated evolution of the monthly excretion of faecal dry matter for the whole herd of the village, (B) Faecal dry matter for the herd of a cattle farmer from Resource Group 1 (RG1) and for herd of a cattle farmer from Resource Group 2 (RG2), (C) Excreted N for herd of cattle farmer from RG1 and RG2 in the 10 year baseline scenario, (D) Accumulated faecal dry matter and crop residues in the kraal of RG1 and RG2.

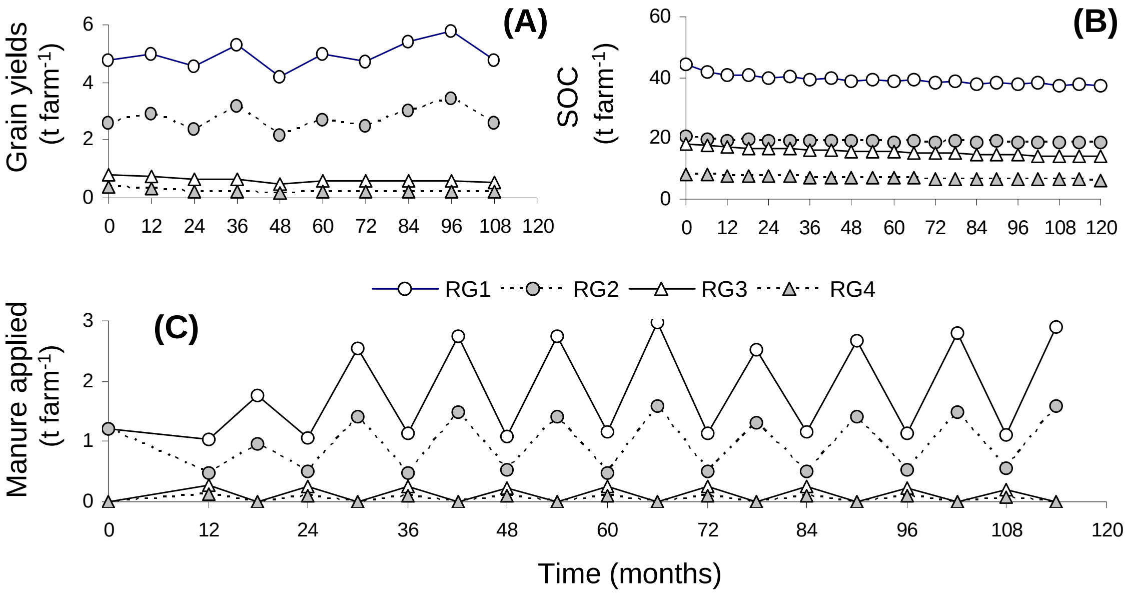



Figure 6: (A) Simulated grain yields for each of the resource groups, cattle farmers (RG1 and RG2) and for the non-cattle farmers (RG3 and RG4), (B) Simulated development of the soil C stock in the farms of each of the resource groups, (C) Simulated amounts of manure applied in the fields of each of the resource groups. These amounts include the application of compost by the farmers plus the direct dejection of cattle on cropland while grazing. The results are for to the baseline scenario..

Grain yields of the RG1 and RG2 followed the pattern of rainfall variability, with an average maize yield of 3.9, 1.2 and 0.6 t grain $ha^{-1}$ in homefields, midfields and outfields of the RG1, and 4, 0.3 t grain $ha^{-1}$ in the homefields and mid and outfields of the RG2. For the non-cattle owners (RG3 and RG4), grain yields were much lower (0.5−1 t grain $ha^{-1}$ in homefields and 0.1−0.3 in the outfields t $ha^{-1}$) and showed little variation from one year to the other. The greater production of the homefields of RG1 and RG2 were due the annual additions of about 2 to 4 t manure $ha^{-1}$ $y^{-1}$ and fertiliser applications of about 40−50 kg N $ha^{-1}$, and 7−10 kg P $ha^{-1.}$ These observed rates of application of fertiliser (Zingore et al., 2007b) are much lower than the blanket recommendations of 120 kg N $ha^{-1}$, and 30 kg P $ha^{-1}$ (Chuma et al., 2000). Grant (1976) recommended the application of 10 t manure $ha^{-1}$ to maintain the productivity of the sandy soils of the communal areas of Zimbabwe. Experiments conducted over 10 years by Rodel and Hopley (1973) indicated that 6 cattle (tropical livestock units) are needed to provide the 10 t of manure needed per hectare of cropland. According to the model simulations, the whole herd of the village with average size of 187 animals transferred 100 t faecal dry matter per year from grasslands to cropland. With minimum losses, that amount will not suffice for 10% of the 116 ha of cropland, if it were to be applied at the recommended rates. Due to the harvest of grain and the removal of most crop residues by grazing cattle, the soil C stocks of all farm types had a negative change at the end of the simulations (Fig. 6B). The smallest decreases (−0.5 t C $ha^{-1}$ in 10 years) were observed in the homefields of RG1 and RG2 that were able to partially compensate for the removal of C through the addition of manure (Fig. 6C). The rest of the fields, that is the homefields of crop farmers RG3 and RG4 and the outfields of all farm types, showed changes of −1.5 to −3 t C $ha^{-1}$ in the 10 years simulation period. The direct dejection of cattle while grazing cropland was small (less than 0.2 t manure $ha^{-1}$) and did not compensate for the removal of C in the residues.

Table 3: Main soil characteristics for the different field types of the different farm types of the virtual village. SOC=Soil Organic Carbon, TSN=Total Soil N, CEC=Cation Exchange Capacity, Ext.P=Extractable P.

| Farm type | Field type | Area (ha) | Clay +Silt (%) | Sand (%) | Bulk density (kg $dm^{-3}$) | SOC (g $kg^{-1}$) | TSN (g $kg^{-1}$) | CEC ($cmol_c$ $kg^{-1}$) | Ext.P (mg $kg^{-1}$) | pH (1:2.5 water) |
|---|---|---|---|---|---|---|---|---|---|---|
| RG1 | Homefield | 0.8 | 12 | 88 | 1.42 | 5.6 | 0.60 | 4.5 | 8 | 5.2 |
| | Midfield | 0.8 | 14 | 86 | 1.45 | 4.8 | 0.43 | 3.0 | 6 | 4.8 |
| | Outfield | 1.7 | 15 | 85 | 1.51 | 4.1 | 0.41 | 1.5 | 4 | 4.7 |
| | Garden | 0.2 | 59 | 41 | 1.28 | 14 | 1.2 | 27 | 23 | 5.8 |
| RG2 | Homefield | 0.6 | 9 | 91 | 1.43 | 6 | 0.62 | 3 | 9 | 5.4 |
| | Midfield | 0.4 | 11 | 89 | 1.55 | 3 | 0.53 | 4 | 5 | 4.5 |
| | Outfield | 1.2 | 8 | 92 | 1.52 | 2.2 | 0.22 | 2 | 4 | 4.2 |
| | Garden | 0.2 | 65 | 35 | 1.31 | 16 | 1.8 | 33 | 17 | 5.9 |
| RG3 | Homefield | 0.4 | 13 | 87 | 1.48 | 4 | 0.45 | 3 | 4 | 5.0 |
| | Midfield | 0.6 | 15 | 85 | 1.47 | 3.7 | 0.34 | 2 | 5 | 3.8 |
| | Outfield | 0.7 | 15 | 85 | 1.43 | 3.3 | 0.31 | 2 | 3 | 4.1 |
| | Garden | 0.2 | 64 | 36 | 1.35 | 13 | 0.9 | 24 | 32 | 5.5 |
| RG4 | Homefield | 0.4 | 12 | 88 | 1.56 | 3.8 | 0.36 | 2 | 5 | 4.7 |
| | Outfield | 0.4 | 14 | 86 | 1.49 | 3 | 0.29 | 3 | 3 | 3.9 |
| | Garden | 0.1 | 53 | 47 | 1.26 | 15 | 1.7 | 32 | 31 | 6.2 |

## 3.2 The effect of different management strategies (scenarios)

### *3.2.1 Effects on the productivity of cattle*

We compared the baseline with the three alternative management scenarios. When crop farmers (RG3 and RG4) impeded the access to cattle to graze their crop residues, the herd growth was restricted, and the weight losses during the late dry season were more pronounced, resulting in lower calving rates. The cumulative effect was a reduction in 20% in herd size as compared with the baseline. The crop residues produced by the crop farmers represented 30% of the total crop residue of the village, and were mostly removed from the fields by the farmers to use as mulch in the vegetable gardens or the residues were consumed in the field by the herd in the baseline scenario. The intake of crop residues was reduced by about 25% when crop farmers did not grant access to cattle to their fields.

The supplementation of the diet of calves and cows with legumes, and the targeted fertilisation scenarios had a positive effect in the herd growth with an increase of 10% and 20% compared with the baseline (Table 4). Farmers from RG1 had on average 3−4 cows, while RG2 had on average 1−2 cows. For the whole herd on average 30% and 60% of the cows were in milk during the dry and rainy season, respectively, for the baseline scenario. The supplementation had a modest effect the amount of milk produced on each farm. Supplementing the cows with small amounts of legumes during the dry season increased the milk yields per day, but the overall effect was small because of the small number of cows in milk during the dry season. It is estimated that the local breeds of calves consume about half of what their dam produces per day (Pedersen and Madsen, 1998), so that the expected benefit of the supplementation in terms of milk for the household would be small. Still, improving the condition of the cows and calves, allowed a faster herd growth, which would justify the production of about 0.7−0.8 t $y^{-1}$ of legume hay for supplementation.

The targeted fertilisation scenario had a positive effect on herd productivity by increasing the availability of crop residues during the dry season. Although cattle were not allowed to graze the homefields of any of the farmers in the village in this scenario, the larger production of biomass of the mid and outfields as compared with the baseline scenario, allowed the herd to grow in number and in bodyweight. The midfields and outfields occupy the 63% of the cropland, and produced on average 32% of the 135 t $y^{-1}$ of crop residues of the village in the baseline, and 55% of the 283 t $y^{-1}$ in the targeted fertilisation scenario. This explains the increase in crop residue intake during the dry season in the latter scenario.

*3.2.2 Effects on crop productivity*

The reduced intake of cattle when they could not access the crop residues of the crop farmers (RG3 and RG4) had a relatively small negative effect on the amount of manure that accumulated in the kraal and could later be recycled in the cropland. Crop production and yields of the cattle farmers of RG1 and RG2 were not much affected when the crop residues on RG3 and RG4 farms were not available for grazing (Table 4). Mtambanengwe and Mapfumo (2005) observed in a village at Murewa that the amounts of standing crop maize residues in the fields at the end of the dry season were not different between farmers of different wealth class and were less than 0.5 t ha$^{-1}$ as compared with the 1.0−1.5 t ha$^{-1}$ standing at the beginning of the dry season. This reduction in biomass was attributed to free-ranging cattle. The remaining residues were about a third of that needed to increase SOC significantly in tropical soils (Palm et al., 2001b). The annual addition of 0.7−1.7 t ha$^{-1}$ crop residues to the poor soils of the non-cattle farmers, resulted in an increase in crop yields, and in the soil C stocks in the long term (Fig. 7B), but still this increase of 40−50% in the farm production of grain, would not suffice to cover the household needs. A family of 6 people needs about 1.5−1.7 t of maize grain y$^{-1}$ to meet their energy requirements. The crop farmers of RG3 and RG4 produced in the 'no access to cattle scenario' 1.0 and 0.4 t maize y$^{-1}$, respectively.

In the targeted fertilisation scenario, the continuous incorporation of crop residues to the homefields (between 3.7−4.0 t dm ha$^{-1}$ y$^{-1}$), the application of small doses of manure (0.7−0.8 t dm ha y$^{-1}$) to mid and outfields, and increased fertilisation rates of N and P (30 and 15 to homefields and 60 and 30 kg N and P ha$^{-1}$ y$^{-1}$ to mid and out-fields) increased the grain production of the farms of RG1 and RG2 threefold, and the soil C stocks by about 7−11 t per ha$^{-1}$ at the end of the simulation (Fig. 7C). Under this scenario, 41% of the cropland was manured, receiving a cumulative application of manure of 11−16 t ha$^{-1}$ in a 10 y period. This is of course a simplification of how the management scenario may be implemented in practice because farmers may opt to apply larger amounts of manure in a scheme designed to rehabilitate soils. The increased soil C stocks of the homefields of crop farmers from RG3 and RG4 due to the incorporation of crop residues (3 t dm ha y$^{-1}$) and application of 60 and 30 kg N and P ha$^{-1}$ y$^{-1}$ to all their fields, increased the grain production of the farm by 6−7 times. In practice, the benefit of the targeted fertilisation scenario may be limited by the availability of oxen to practice winter ploughing and incorporate the residues into the soil, and the willingness of cattle owners to share their oxen during the early dry season when this is possible. The farmers that may incorporate the crop residues to the soils are those that need the residues to feed their cattle during the dry season. The benefits of the targeted fertilisation in combination with management of the organic resources look promising for improving crop production at farm and village level. However, we are aware of the limitations of our modelling approach in simulating long term response to continuous addition of organic residues on poor sandy soils that may overestimate the crop responses (Tittonell et al., 2007). These results need to be inspected against long term experimental data, a task that is being undertaken by local research in the area of study (Zingore et al., 2007a), and the effectiveness of this targeted fertility management remains to be tested together with farmers.

Table 4: Livestock and crop productivity, manure excreted, collected and applied, and crop residues incorporated for each of the farm types (resource groups). Averages and standard deviations of the last 5 years of the 10 y simulations for the baseline scenario using the average rainfall series.

| | Herd size (# $farm^{-1}$) | Live weight (kg $farm^{-1}$) | Grass intake (t $farm^{-1} y^{-1}$) | Crop residues intake (t $farm^{-1} y^{-1}$) | Milk produced (kg $farm^{-1} y^{-1}$) | Manure enters the kraal (t $farm^{-1} y^{-1}$) | Crop residues to kraal (t $farm^{-1} y^{-1}$) | Total manure applied (t $farm^{-1} y^{-1}$) | Maize stover produced (t $farm^{-1} y^{-1}$) | Crop residues to soils (t $farm^{-1} y^{-1}$) | C stock (t $farm^{-1}$) | Grain produced (t $farm^{-1} y^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *<u>Baseline</u>* | | | | | | | | | | | | |
| RG1 | 11.9 ± 0.3 | 3316 ±225 | 21.1 ±2.7 | 7.4 ±0.5 | 1526 ±220 | 7.0 ±0.5 | 0.8 ±0.2 | 2.9 (3.9)[1] | 6.7 (2.0)[2] | < 0.5 | 38.1 (11.5) | 5.1 (1.5) |
| RG2 | 6.1 ± 0.2 | 1660 ±139 | 10.7 ±1.6 | 3.7 ±0.3 | 830 ±119 | 3.5 ±0.3 | 0.6 ±0.1 | 1.6 (2.0) | 3.3 (1.5) | < 0.5 | 18.8 (9.4) | 2.9 (1.4) |
| RG3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0.2) | 1.3 (0.7) | < 0.3 | 14.6 (8.6) | 0.6 (0.4) |
| RG4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0.1) | 0.5 (0.6) | < 0.3 | 6.5 (8.2) | 0.2 (0.3) |
| *<u>Crop farmers conserve their crop residues</u>* | | | | | | | | | | | | |
| RG1 | 10.6 ± 0.3 | 2859 ±159 | 19.2 ±2.0 | 5.5 ±0.5 | 1336 ±174 | 6.0 ±0.4 | 0.8 ±0.1 | 2.6 (3.7) | 6.7 (2.0) | < 0.3 | 38.0 (11.5) | 5.1 (1.5) |
| RG2 | 5.4 ± 0.1 | 1414 ±87 | 9.6 ±1.1 | 2.7 ±0.3 | 722 ±95 | 2.9 ±0.2 | 0.6 ±0.1 | 1.4 (1.9) | 3.3 (1.5) | < 0.3 | 18.7 (9.4) | 2.8 (1.3) |
| RG3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0) | 1.8 (1.1) | 1.7 (1.0) | 18.5 (10.9) | 1.0 (0.6) |
| RG4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0) | 0.8 (1.0) | 0.7 (0.9) | 8.3 (10.4) | 0.4 (0.5) |
| *<u>Legumes supplemented</u>* | | | | | | | | | | | | |
| RG1 | 12.8 ± 0.4 | 3713 ±313 | 23.0 ±3.5 | 7.5 ±0.6 | 1796 ±363 | 7.7 ±0.7 | 0.8 ±0.1 | 3.3 (4.2) | 6.7 (2.0) | < 0.5 | 38.1 (11.5) | 5.1 (1.5) |
| RG2 | 6.5 ± 0.2 | 1859 ±165 | 11.5 ±1.8 | 3.7 ±0.3 | 902 ±153 | 3.8 ±0.4 | 0.6 ±0.1 | 1.7 (2.1) | 3.3 (1.5) | < 0.5 | 18.9 (9.4) | 2.9 (1.4) |
| RG3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0.2) | 1.3 (0.7) | < 0.3 | 14.6 (8.6) | 0.6 (0.4) |
| RG4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0.1) | 0.5 (0.6) | < 0.3 | 6.5 (8.2) | 0.2 (0.3) |
| *<u>Targeted fertilisation</u>* | | | | | | | | | | | | |
| RG1 | 13.6 ± 0.4 | 3939 ±325 | 23.3 ±3.6 | 9.8 ±0.5 | 1853 ±258 | 8.1 ±0.7 | 0.7 ±0.1 | 3.4 (4.5) | 13.0 (3.9) | 3.4 (1.0) | 49.0 (14.9) | 12.6 (3.6) |
| RG2 | 7.0 ± 0.4 | 1990 ±183 | 11.9 ±2.0 | 5.0 ±0.3 | 958 ±124 | 4.0 ±0.6 | 0.4 ±0.1 | 1.8 (2.0) | 5.4 (2.5) | 2.6 (1.2) | 25.3 (12.7) | 4.4 (2.2) |
| RG3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0.4) | 4.4 (2.6) | 1.6 (0.9) | 20.0 (11.8) | 3.9 (2.3) |
| RG4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0.2) | 2.1 (2.6) | 1.0 (1.2) | 9.5 (11.9) | 1.8 (2.2) |

[1] Total manure applied direct dejection plus addition of compost
[2] Between parentheses expressed in a per ha basis

Table 5: Livestock and crop productivity, manure excreted, collected and applied, and crop residues incorporated for each of the farm types (resource groups). Averages and standard deviations of the last 5 years of the 10 y simulations for the baseline scenario using the wetter rainfall series.

| | Herd size (# farm$^{-1}$) | Live weight (kg farm$^{-1}$) | Grass intake (t farm$^{-1}$y$^{-1}$) | Crop residues intake (t farm$^{-1}$y$^{-1}$) | Milk produced (kg farm$^{-1}$ y$^{-1}$) | Manure enters the kraal (t farm$^{-1}$ y$^{-1}$) | Crop residues to kraal (t farm$^{-1}$ y$^{-1}$) | Total manure applied (t farm$^{-1}$ y$^{-1}$) | Maize stover produced (t farm$^{-1}$ y$^{-1}$) | Crop residues to soils (t farm$^{-1}$y$^{-1}$ ) | C stock (t farm$^{-1}$) | Grain produced (t farm$^{-1}$ y$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Baseline* | | | | | | | | | | | | |
| RG1 | 13.6 ± 0.4 | 3715 ±413 | 24.5 ±1.7 | 7.5 ±1.6 | 2049±115 | 7.9 ±0.3 | 0.9 ±0.2 | 3.3 (4.3)[1] | 6.6 (2.0) [2] | < 0.5 | 38.4 (11.6) | 5.2 (1.6) |
| RG2 | 6.9 ± 0.3 | 1844 ±198 | 12.2 ±0.8 | 3.7 ±0.8 | 1106 ±60 | 3.9 ±0.2 | 0.6 ±0.1 | 1.8 (2.2) | 3.4 (1.7) | < 0.5 | 19.0 (9.5) | 3.0 (1.5) |
| RG3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0.2) | 1.2 (0.7) | < 0.3 | 14.6 (8.6) | 0.5 (0.3) |
| RG4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0.1) | 0.5 (0.6) | < 0.3 | 6.5 (8.2) | 0.2 (0.2) |
| *Crop farmers conserve their crop residues* | | | | | | | | | | | | |
| RG1 | 12.2 ± 0.3 | 3285 ±339 | 22.7 ±1.1 | 5.7 ±1.4 | 1801 ±55 | 7.0 ±0.2 | 0.9 ±0.1 | 3.0 (4.0) | 6.6 (2.0) | < 0.3 | 38.4 (11.6) | 5.1 (1.6) |
| RG2 | 6.1 ± 0.1 | 1595 ±169 | 11.1 ±0.6 | 2.8 ±0.7 | 951 ±43 | 3.3 ±0.1 | 0.7 ±0.1 | 1.6 (2.0) | 3.4 (1.7) | < 0.3 | 19.0 (9.5) | 3.0 (1.5) |
| RG3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0) | 1.7 (1.0) | 1.6 (1.0) | 18.6 (11.0) | 0.9 (0.5) |
| RG4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0) | 0.8 (1.0) | 0.7 (0.9) | 8.4 (10.5) | 0.4 (0.5) |
| *Legumes supplemented* | | | | | | | | | | | | |
| RG1 | 14.6 ± 0.7 | 4193 ±494 | 26.6 ±2.0 | 7.5 ±1.7 | 2160 ±96 | 8.7 ±0.4 | 0.9 ±0.4 | 3.6 (4.7) | 6.7 (2.0) | < 0.5 | 38.7 (11.7) | 5.2 (1.6) |
| RG2 | 7.3 ± 0.4 | 2095 ±239 | 13.3 ±1.0 | 3.8 ±0.8 | 1164 ±63 | 4.3 ±0.2 | 0.7 ±0.2 | 1.9 (2.4) | 3.4 (1.7) | < 0.5 | 19.2 (9.6) | 3.0 (1.5) |
| RG3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0.2) | 1.2 (0.7) | < 0.3 | 14.6 (8.6) | 0.5 (0.3) |
| RG4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0.1) | 0.5 (0.6) | < 0.3 | 6.5 (8.2) | 0.2 (0.2) |
| *Targeted fertilisation* | | | | | | | | | | | | |
| RG1 | 14.5 ± 0.7 | 4157 ±412 | 25.8 ±2.0 | 9.6 ±1.4 | 2212 ±111 | 8.7 ±0.3 | 0.8 ±0.1 | 3.5 (4.9) | 12.8 (3.9) | 3.2 (1.0) | 49.8 (15.1) | 12.4 (3.7) |
| RG2 | 7.5 ± 0.4 | 2118 ±202 | 13.3 ±1.0 | 4.9 ±0.7 | 1194 ±82 | 4.4 ±0.2 | 0.5 ±0.1 | 1.8 (2.1) | 5.4 (2.7) | 2.6 (1.3) | 26.1 (13.0) | 4.7 (2.4) |
| RG3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0.4) | 4.1 (2.4) | 1.4 (0.8) | 20.0 (11.8) | 3.7 (2.2) |
| RG4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0.2) | 2.0 (2.4) | 1.0 (1.0) | 9.5 (11.9) | 1.7 (2.1) |

[1] Between parenthesis total manure applied direct dejection plus addition of compost
[2] Between parentheses expressed in a per ha basis

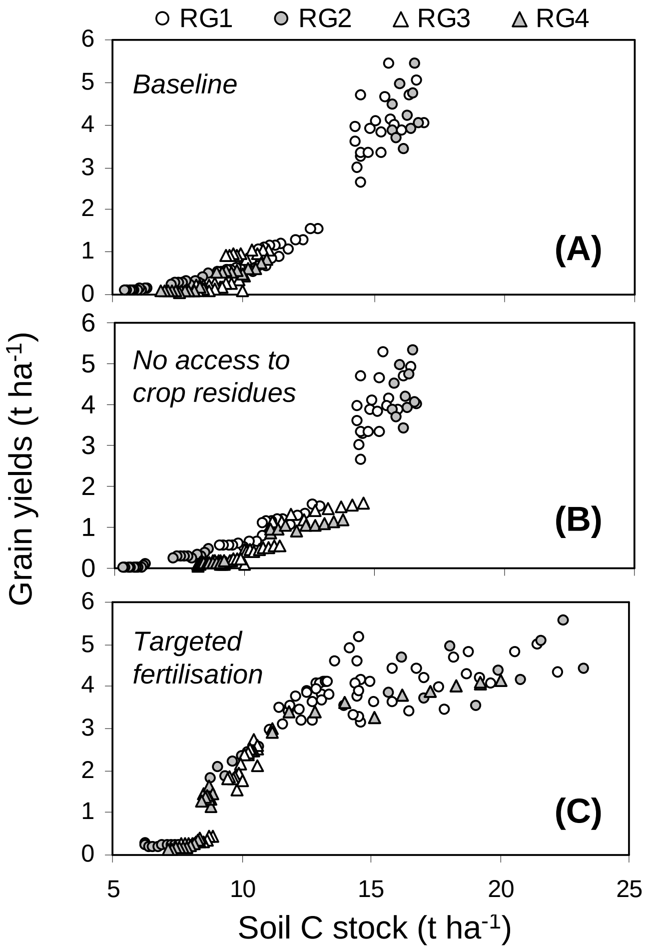



Figure 7: Simulated grain yields plotted against simulated soil C stock at each plot type for the cattle farmers of Resource Groups 1 and 2 (RG1 and RG2), and for the non-cattle farmers (RG3 and RG4), for the three different scenarios: (A) Baseline, (B) The cattle of the RG1 and RG2 has no access to the residues of RG3 and RG4, and (C) Targeted fertilisation scenario, where all crop residues of the homefields are incorporated into the soil, manure is applied to the mid and outfields and fertiliser use in all of the plots is increased (see Section 2.4 for details on the scenarios).

### 3.3 The effect of rainfall variability on the expected benefits of management

The coefficient of variation of rainfall and the probability of seasonal drought are relatively high for Murewa therefore in this section we compared the outcome of the explorations by using three different rainfall series, for all the management scenarios.

*3.3.1 The effect on the herd dynamics and cattle productivity*

The herd dynamics differed for each of the three different rainfall sets used in the simulations due to feed availability (Fig. 8). The effect of restricted access to the crop residues of the crop farmers was observed under all three rainfall series, though this was more critical for the herd size when the start of the rains was delayed (e.g month 60 in Figs. 8A and D and month 48 in Figs. 8C and D).

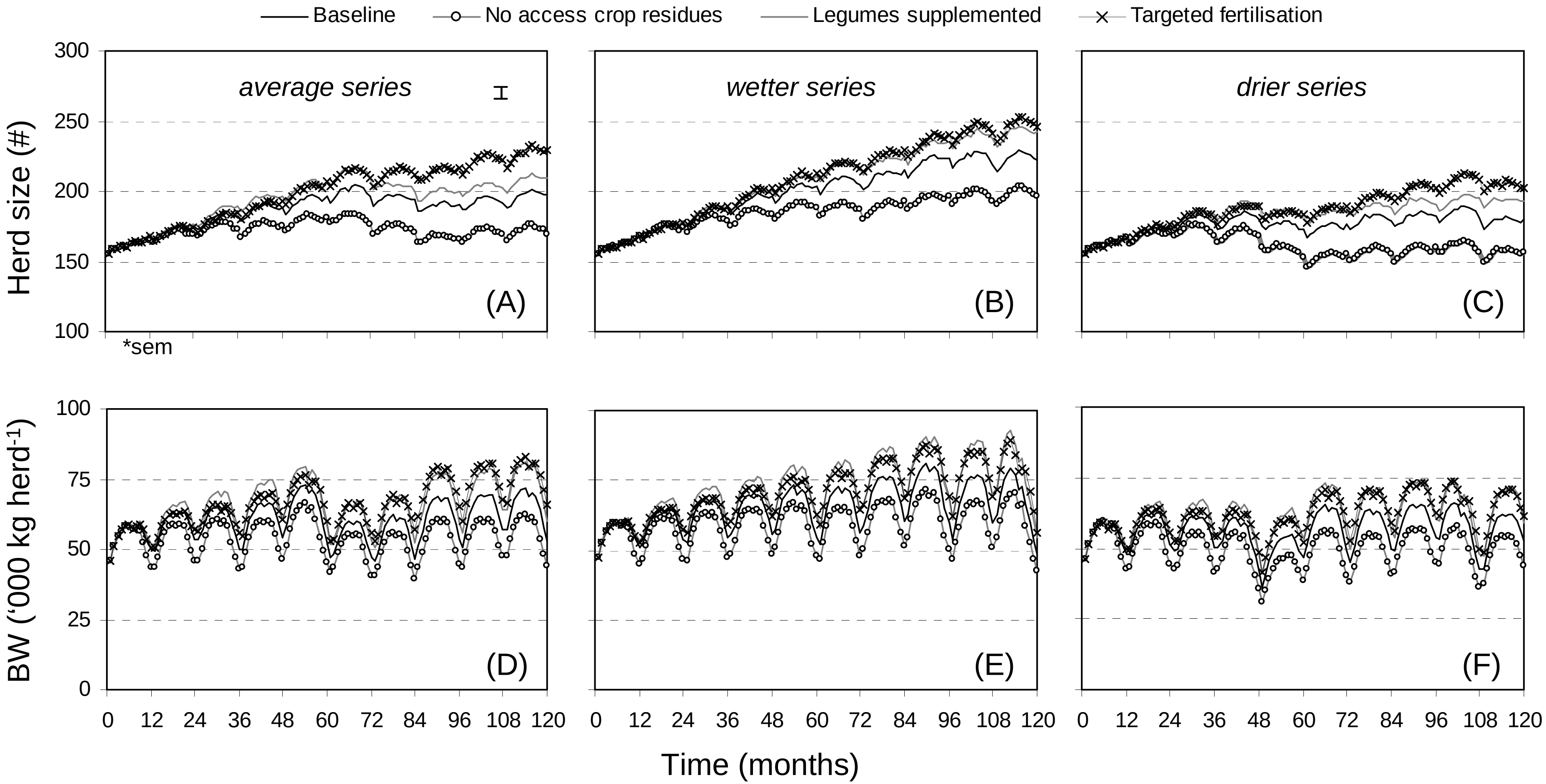



Figure 8: Simulated development of the herd size and aggregated bodyweight of the whole herd of the village under three different management scenarios (baseline, no access to cattle to the crop residues of crop farmers, and the targeted scenario), and with different rainfall series (A) and (D) using an average rainfall series, (B) and (E) using a wetter series, and (C) and (F) using a drier series.

In the model, feed availability in the grasslands is driven by rainfall, in the dry season cattle feed crop residues and grass of the vlei (the more humid landscape position of the grassland), but intake is restricted due to the poor quality of the grass. When the availability of crop residues is reduced, cattle lose weight more rapidly, and may die due to starvation, according to the model, when the beginning of the rainy season is delayed. This must be taken with caution because the model keeps track of the feed resources available within the area described by farmers as their area of exploitation under normal circumstances. Although the level of feed resources utilisation, both from grassland and crop residues of our study agree with other previous studies in Zimbabwe (e.g. Steinfeld, 1988), we did not include alternative adaptive strategies of farmers that minimise death of cattle such as moving the herd to a different area where forage availability may be higher, or destock when the season becomes critically dry. When two drought years occur together this results in major loss of cattle, as was observed in Zimbabwe during the catastrophic drought period between 1991 and 1992 (Scoones et al., 1996) and occurs also when we simulated cattle numbers using the rainfall received in Murewa over this period.

Supplementing calves and lactating cows with legumes had a positive effect in the population size because these were added to diet when this is very poor in protein, reducing the bodyweight losses and preserving young and females in the herd. Smallholders make use of compensatory growth by allowing the animals to gain weight during the rainy season and to lose weight during the dry season because supplementation tends to be uneconomic (Kebreab et al., 2005). Supplementation of protein during the rainy season can increase the rate of growth and compensation up to 2−3 kg per day for cattle (Ørskov and Hovell, 1986). This appears as an option to secure the herd numbers, but needs to be analysed in terms of benefit and constrains (cost, competition with other labour needs) within other livelihood options at farm scale.

### *3.3.2 The effect on the intensity of the interactions*

Rainfall variability has a large effect on feed availability, which generates feedbacks into the crop-livestock system by having an effect on the herd dynamics, the intake of grass and crop residues from the cropland, and the amount of C and nutrients that is transferred from grassland to the farms. In the simulations when there was little rainfall during the growing season, the recovery of bodyweight of the herd was poor, and animals entered the dry season in a poor condition that, added to the low availability of crop residues, risked the survival of the animals. When the production of grass is adequate, but feed availability during dry season is low, the effect of a delay in the start of the rains can decrease the survival of cattle in the short term and have negative consequences on the reproduction capacity of females in the medium and longer term. This effect was observed in herd sizes and live weight of the herds in the simulation in the scenario of no access for cattle to the crop residues of crop farmers in the drier rainfall series (Table 6). On the other hand, the positive effect of the rainfall from the wetter series was observed in terms of cattle productivity (numbers, bodyweight, milk and manure), but not in large changes in soil C in the soils, because the extra biomass produced due to higher rainfall and manure availability was consumed by the larger herd. In the baseline scenario, cattle consumed more crop residues than that produced at the farms where they belong, this deficit being larger for the RG1 farmers and in the wetter rainfall series (Tables 4, 5 and 6). In the targeted fertilisation scenario, although the RG1 and RG2 farmers produced enough crop residues to feed their cattle, because they incorporate most of the crop residues into the soils of their homefields, cattle fed more on the crop residues of the non-cattle farmers (RG3 and RG4) leaving smaller amounts to be incorporated into the soils of their mid and outfields.

In the wetter rainfall series, and for all scenarios, the transfer of C as manure from the grassland to cropland was 10 % larger (between 105 to 115 t manure $y^{-1}$ for the whole village *vs* 80−102 t manure $y^{-1}$ for the drier series). The transfer from the fields of crop farmers to the kraals of cattle farmers is also larger in the baseline of the wetter series, but this effect is not perceived as a loss in soil C because of the larger biomass production in the years of more rainfall and the larger additions of manure that partly compensate for the removals (Fig. 9A).

The positive effects of incorporating residues and applying manures were only slightly larger in the wetter rainfall series (Fig. 9B and C), because the differences in biomass added to soils was relatively small. Rainfall variability has a relatively small effect on soil processes which have relatively slow rates, but the effect on crop yields and on people food security can be large. Under the baseline scenario, in which the village as a whole applied 2.3 and 0.4 t $y^{-1}$ of N and P mineral fertilisers, the grain production fluctuated around 100 t of grain (Fig. 10A), which is, in principle, sufficient to feed a village with 330 people (with an average need of 300 kg maize per capita per year). In a dry year, production of grain fell by half (Fig. 10C), leaving most people food insecure. Crop farmers of RG3 and RG4, who represented 60% of the village population, produced under the baseline scenario about 15−20% of the total grain (Fig. 10 D, E and F), in all three rainfall series. When these crop farmers did not grant access to cattle to graze their crop residues, the overall grain production of the village slightly increased, and the share of the production of the crop farmers rose to about 25%, which was not enough to make them food self-sufficient (cf. Tables 4, 5 and 6). Under the targeted fertilisation scenario where - rather optimistically - the production of grain more than doubled, the share of the crop farmers increased to about the half of the total, and would have reached food security for most of the years. This intervention would imply increasing the use of mineral fertiliser 2.5 times for N from 2.3 to 5.8 t $y^{-1}$, and the use of P sevenfold, from 0.4 to 2.9 t $y^{-1}$. At the village level, this would mean putting into practice the aspiration of the African green revolution of using about 50 kg of fertiliser per ha of cropland and manuring about 40% of the land.

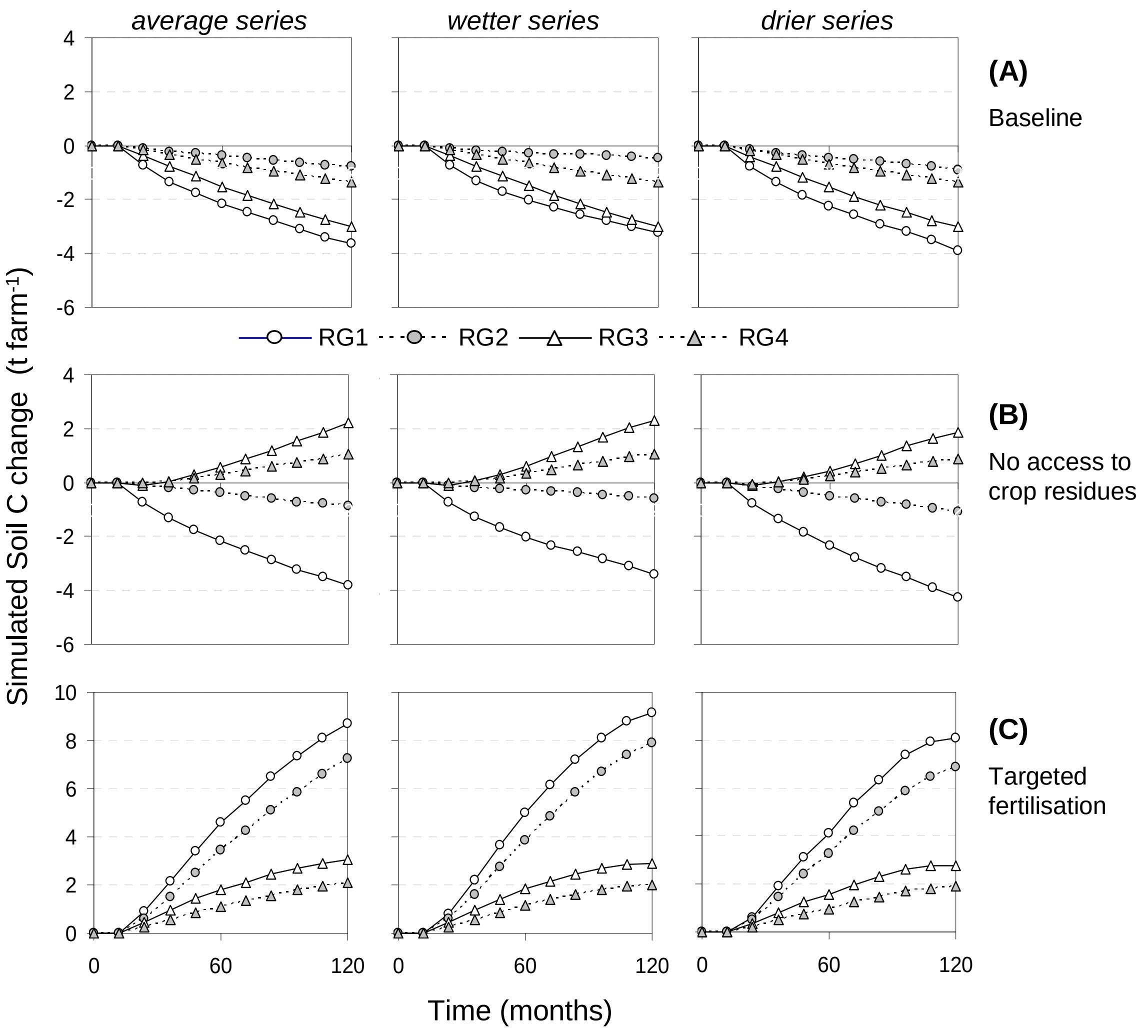



Figure 9: Simulated changes in soil organic C (with respect to the year 0) after 10 years of cultivation under different management strategies: (A) Baseline, (B) No access to cattle to the crop residues of the non-cattle farmers (RG3 and RG4), and (C) Targeted fertilisation scenario where all crop residues of the homefields are incorporated into the soils, manure is applied to the mid and outfields and the fertiliser use in all the plots is increased (see Section 2.4 for details on the scenarios).

Table 6: Livestock and crop productivity, manure excreted, collected and applied, and crop residues incorporated for each of the farm types (resource groups). Averages and standard deviations of the last 5 years of the 10 y simulations for the baseline scenario using the drier rainfall series.

| | Herd size (# farm$^{-1}$) | Live weight (kg farm$^{-1}$) | Grass intake (t farm$^{-1}$y$^{-1}$) | Crop residues intake (t farm$^{-1}$y$^{-1}$) | Milk produced (kg farm$^{-1}$ y$^{-1}$) | Manure enters the kraal (t farm$^{-1}$ y$^{-1}$) | Crop residues to kraal (t farm$^{-1}$ y$^{-1}$) | Total manure applied (t farm$^{-1}$ y$^{-1}$) | Maize stover produced (t farm$^{-1}$ y$^{-1}$) | Crop residues to soils (t farm$^{-1}$y$^{-1}$) | C stock (t farm$^{-1}$) | Grain produced (t farm$^{-1}$ y$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Baseline* | | | | | | | | | | | | |
| RG1 | 10.9 ± 0.2 | 3147 ±291 | 20.7 ±1.7 | 7.0 ±1.5 | 1515 ±121 | 6.6 ±0.5 | 0.8 ±0.2 | 2.7 (3.8)[1] | 6.3 (1.9)[2] | < 0.5 | 38.0 (11.5) | 4.8 (1.5) |
| RG2 | 5.7 ± 0.1 | 1562 ±146 | 10.3 ±0.8 | 3.5 ±0.8 | 808 ±55 | 3.2 ±0.2 | 0.6 ±0.1 | 1.5 (1.9) | 3.2 (1.6) | < 0.5 | 18.7 (8.5) | 2.7 (1.4) |
| RG3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0.2) | 1.2 (0.7) | < 0.3 | 14.5 (8.6) | 0.5 (0.3) |
| RG4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0.1) | 0.5 (0.6) | < 0.3 | 6.5 (8.2) | 0.2 (0.2) |
| *Crop farmers conserve their crop residues* | | | | | | | | | | | | |
| RG1 | 9.6 ± 0.2 | 2631 ±198 | 18.1 ±1.2 | 5.1 ±1.2 | 1289 ±67 | 5.5 ±0.4 | 0.8 ±0.2 | 2.7 (3.4) | 6.2 (1.9) | < 0.3 | 37.6 (11.4) | 4.7 (1.4) |
| RG2 | 4.9 ± 0.1 | 1332 ±106 | 9.2 ±0.6 | 2.6 ±0.2 | 705 ±39 | 2.4 ±0.2 | 0.6 ±0.1 | 1.3 (1.8) | 3.1 (1.6) | < 0.3 | 18.6 (8.4) | 2.7 (1.3) |
| RG3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0) | 1.7 (1.0) | 1.5 (0.9) | 18.3 (10.8) | 0.9 (0.5) |
| RG4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0) | 0.7 (0.9) | 0.7 (0.8) | 8.2 (10.3) | 0.4 (0.5) |
| *Legumes supplemented* | | | | | | | | | | | | |
| RG1 | 11.9 ± 0.1 | 3509 ±364 | 22.4 ±2.3 | 7.1 ±1.5 | 1623 ±302 | 7.3 ±0.5 | 0.8 ±0.2 | 3.1 (4.0) | 6.3 (1.9) | < 0.5 | 38.1 (11.5) | 4.9 (1.5) |
| RG2 | 6.0 ± 0.2 | 1731 ±180 | 11.1 ±1.1 | 3.5 ±0.8 | 823 ±68 | 3.6 ±0.2 | 0.6 ±0.2 | 1.6 (2.1) | 3.2 (1.6) | < 0.5 | 18.8 (8.5) | 2.8 (1.4) |
| RG3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0.2) | 1.2 (0.7) | < 0.3 | 14.5 (8.5) | 0.5 (0.3) |
| RG4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0.1) | 0.5 (0.6) | < 0.3 | 6.5 (8.1) | 0.2 (0.2) |
| *Targeted fertilisation* | | | | | | | | | | | | |
| RG1 | 12.2 ± 0.3 | 3604 ±351 | 22.2 ±2.0 | 9.2 ±1.2 | 1723 ±199 | 7.4 ±0.5 | 0.7 ±0.2 | 3.0 (4.3) | 12.1 (3.7) | 3.1 (1.0) | 48.7 (14.8) | 11.6 (3.5) |
| RG2 | 6.4 ± 0.2 | 1810 ±182 | 11.2 ±1.0 | 4.7 ±0.6 | 923 ±94 | 3.7 ±0.2 | 0.4 ±0.1 | 1.5 (1.9) | 5.0 (2.5) | 2.5 (1.1) | 25.2 (11.4) | 4.4 (2.2) |
| RG3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0.4) | 4.1 (2.4) | 1.4 (0.8) | 19.8 (11.6) | 3.6 (2.2) |
| RG4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 (0.1) | 1.9 (2.4) | 0.9 (1.1) | 9.4 (11.7) | 1.7 (2.1) |

[1] Total manure applied direct dejection plus addition of compost
[2] Between parentheses expressed in a per ha basis

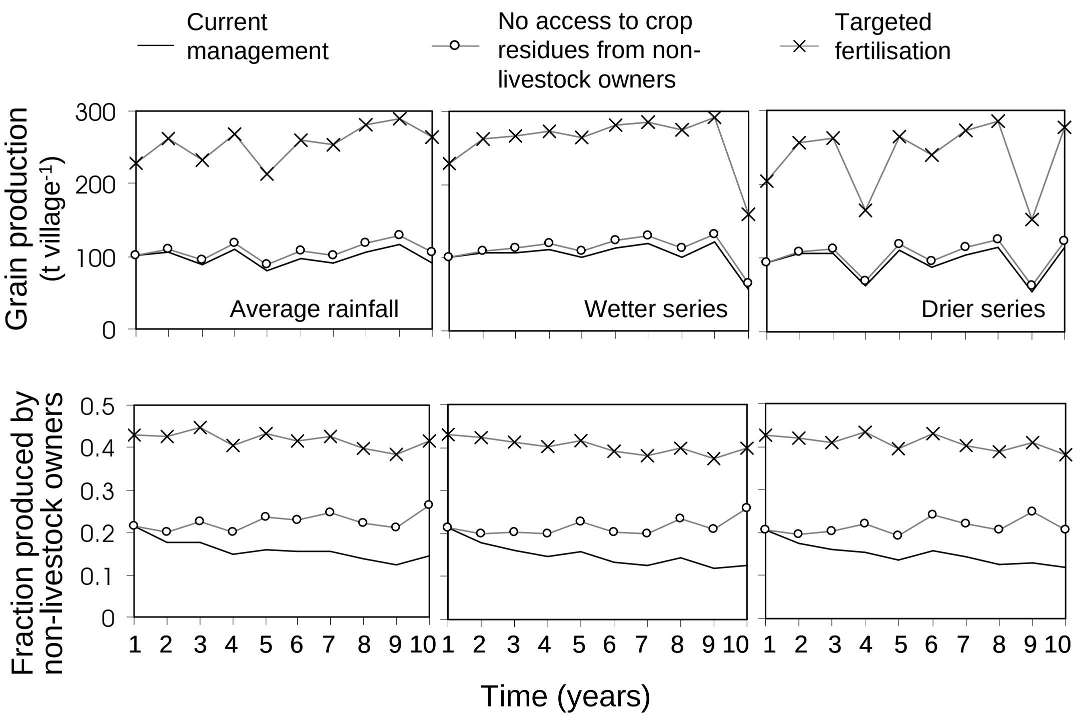



Figure 10: Simulated grain production for the whole 'virtual' village under three management scenarios (baseline, no access to cattle crop residues of the non-cattle farmers (RG3 and RG4), and targeted fertilisation), and using three different rainfall series: (A) average series, (B) a wetter series and (C) a drier series, and the share of the non-cattle farmers grain production to total production of the whole village for (D) average rainfall series, (E) a wetter rainfall series and (F) a drier rainfall series.

### 3.4 Cattle productivity *vs* crop productivity

More than 85% of communal farm households use animal draft power, but only 5−8% of the farmers have sufficient draft animals for traction and this leads either to poor crop yields because of the delays in planting Shumba (1984), or to reduction in the planted areas. A span of two oxen requires about three and a half days to plough a hectare of land on a wet soil Francis (1993). No access to animal traction resulted in delays in planting and failure to perform winter ploughing. Where animal power is not used, weeding can take up to 175 h/ha: this is almost half of the total time required for all the field operations together. According to Spear (1968), maize yields are reduced by 1–3% per day when planting is delayed until mid−November. The village studied had between 40−50 oxen in the simulations across scenarios, which in principle would be enough to plough the 116 ha of cropland within a month, if access to oxen is guaranteed and exchanges between crop and cattle farmers are facilitated.

To sustain the herd size of the baseline scenario, cattle of the farmers from RG1 (in average 10 heads) consumed between 20−25 t of grass biomass $y^{-1}$. The Hyparrhenia-veld type of grassland produces about 1.5 to 4 t biomass $ha^{-1}$ $y^{-1}$ (Frost, 1996), of which about half may actually be consumed by cattle due either to poor quality or constraints imposed by herbage availability (De Ridder and Breman, 1993; Herrero et al., 1998). Without taking into account negative effect of overgrazing on the pastures, each farmer of RG1 would need to have access to 12−27 ha of grassland to apply about 3−4 t of manure $y^{-1}$ (under relatively poor management) in their farms. Under the baseline scenario, it should be possible to maintain the herd size to guarantee the availability of oxen for ploughing.

### 3.5 Options for intensification through crop-livestock integration

Although there is consensus on the need of organic resources to sustain crop production in communal farming areas of Zimbabwe (Campbell et al., 1998; Giller et al., 1998; Waddington et al., 1998; Mapfumo and Giller, 2001), and most researchers agree on the long term effectiveness of manure applications (Grant, 1967; Mugwira et al., 2002; Nyamangara et al., 2003b), recommendations do not match manure availability on the farms of most smallholders. Our study indicates that farmers with 10 cattle may recycle about 4 t manure $y^{-1}$ with the current manure management. These amounts may be increased by adding crop residues, but the quality of the manure compost will be reduced, and the cost of transport back to the field increased. On the other hand, adding crop residues to the compost, reduces feed availability to cattle, which in turns affects manure production. Surveys conducted in communal areas of Zimbabwe (Mugwira and Murwira, 1997) indicated that farmers apply much larger amounts (between 10−20 t manure $farm^{-1}$ $y^{-1}$) than that calculated in our simulations, but manures applied by farmers are usually mixed with large amounts of sand that comes from the bottom of the kraal when manure is dig out, which reduces the quality of the manure compost (Mugwira and Murwira, 1997). Research in Zimbabwe has shown some opportunities to increase manure availability through storing manure in pits instead of in heaps (Nzuma and Murwira, 2000), which may require extra labour. This may reduce the gap between the manure that accumulates during kraaling, which was in our study between 7−8 t manure $farm^{-1}$ $y^{-1}$ for farmers with 10 cattle, and manure applied to crops (3−4 t manure $farm^{-1}$ $y^{-1}$ ), but due to the unimodal rainfall pattern, losses of C and nutrients during may not be as low as the 30% for C and 20% for N observed for optimal manure management in the highlands of East Africa where manures are stored for a period of 6 months (Rufino et al., 2007b - Chapter 3).

Thornton et al (2003) identified a number of crop-livestock management strategies that show promise in increasing income and productivity of smallholders in maize-based mixed cropping systems of Southern Africa. These strategies included improved feeding systems incorporating dry maize stover, improved management of green maize stover for feed use, intercropping with grain, dual-purpose or forage legumes. We need to be aware that increasing the use of crop residues for cattle feeding may bring negative consequences for the non-cattle owners unless this is compensated somehow by social agreements. In the study of Thorne et al. (2002), the benefits of improved manure management strategies for more effective nutrient retention and transfer amongst system components were not as obvious as those from the other strategies. We did not explore in our study the potential benefits of improved manure quality as we were interested in the interaction between farmers due to feeding strategies. This is an interesting research question that needs to be explored at farm scale, taking into account competitive uses for the crop residues and for labour in other farm activities. Sumberg (2002a) discussed that constraint to the benefits of crop-livestock integration need to consider the larger integrated system, and that farmers have shown little interest on increasing the productivity per head of their cattle, because of the different roles attached to cattle. It is necessary to understand who the potential user of technologies are, and which are their objectives, often not related to increase biological productivity. Sumberg (2002a) stressed the need to look at longer term, trends and evolutionary steps in systems development, and such questions can be addressed with the combined models presented here. Producers work within the boundaries of their existing system, and although thinking of new systems configurations is valid, adoption by the producer is in no sense guaranteed. Is it likely that a combination of the scenarios we explored where crop farmers keep their crop residues and cattle farmers producing legumes to allow cattle to consume poor quality grass, may reduce the competition for resources in the community. All these need to be explored together with farmers to see how they fit into their broader livelihoods strategies.

## 5. Concluding remarks

At community scale, the type of interaction between farmers determines who benefits from the integration of crop and livestock. The tolerance of the non-cattle farmers and the removal of C by cattle leads to lower crop yields in the poor fields of their farms, and has relatively smaller effect on the fields of the cattle owners that receive animal manures and fertilisers. Rainfall variability intensifies the interactions, when the start of the rains is delayed, the low availability of crop residues during the dry season may lead to loss of animals from the herd. In years of good rainfall the removal is relatively not important. Farmers make use of common resources according to their own resource endowment (cattle heads) and social agreements. The removal of nutrients from the fields of the non-cattle owners due to grazing cattle was relatively small in our explorations due to the low biomass production of the poorer fields of those farmers. Crop-livestock integration at village scale results in concentration of nutrients in the farms with larger herds and increases dependency of the poorer smallholders on external inputs, and other types of exchanges within the village such as labour for food, cash or manures. In our targeted fertilisation scenario we brought and spread in the village cropland three times more fertiliser than that used at the time of the survey in 2004. This was enough to compensate for the negative effect of the interactions due to feeding management of cattle, and to boost the grain production of the village. It may be an unrealistic scenario for a smallholder community in Zimbabwe, certainly under the current economic and political circumstances. This type of system change needs to be supported by institutional changes, in line with the ideas of the Abuja declaration of the African heads of state and the African Green Revolution.

# Chapter 8

## General discussion

## 1. The benefits of crop-livestock integration

Using the analytical tools developed within this research, different functions of livestock within mixed crop-livestock systems in Sub-Saharan Africa were quantified and evaluated with regard to whether they could be entry points for interventions (see specific objective 2 in Chapter 1). The use of manure and the benefits obtained differ between farming systems from one environment to another depending on the agro-ecology, market opportunities, but also culture and traditions. Gains in nutrients may be obtained through improving manure management, through collection and storage (Chapter 2). The amount of manure available depends on the cattle holdings and feed availability, which are linked to management decisions of the farmers on allocation of resources (land, labour or cash) to either produce, collect or purchase feeds, and to the availability of feed at a higher relevant scale (e.g. village, nearest market).

Farmers may improve feeding if there is an expected benefit from following that strategy (Baltenweck et al., 2004). In dairy systems, this benefit may be measured in calving and milk outputs. Explorations indicated that to maximise benefits from investing in dairy intensive systems, with herds with low replacement rates (Bebe et al., 2003), feeding needed to be targeted to fill nutritional requirements at key physiological stages (Chapter 4). Under the current farm sizes (less than 1 ha), and the proportion of land allocated to fodder crops (about 20%), relatively large amounts of feed need to be imported (30−40% according to Romney et al., 2004) in the intensive systems of Central Kenya. Establishment of dairy systems needs to guarantee not only product price and infrastructure, but also a steady input supply (feeds, replacements, veterinary services, etc) and this has strong implications at the regional scale. With the current mortality rates in the dairy system of Central Kenya, we estimated a reduction in lifetime productivity of dairy cows of 43−65% as compared to the scenario with nil mortality (Chapter 4). Without institutional support in providing extension and veterinary services, investment in animal capital, with a start-up capital for dairy of US$ 400−1000 in the Central highlands of Kenya (Mwangi and Omore, 2004), may not be justified and certainly beyond the reach of most poor farmers.

Beyond the contribution to incomes, dairy systems need to be sustainable. In our explorations (Chapter 4) using different feeding strategies targeted to increase milk output and reduce calving intervals, we observed an increase of about 30% in the amount of manure and of 40% in the amount of manure N between the poorest diet and the best diet, which was supplemented with concentrates to match the energy requirements of lactation (Table 1). Although farmers have different management strategies to increase the quality of the manure before applying to their fields (Lekasi et al., 2003), large losses of C and nutrients during collection and composting reduce considerably the amount available for recycling within the farm (Chapter 3).

We observed differences in N cycling efficiency (NCE) (see specific objective 3 in Chapter 1) between farms of different wealth classes. For poorer farmers, large N losses occur at all stages of manure cycling. With current management, the poor farmer recovered <1 kg N $y^{-1}$ in composted manure from 15 kg N $y^{-1}$ excreted. Improved manure storage had little effect on increasing overall NCE for the poor farmer due to large losses before storage. Wealthier farmers can expect benefits from improving manure storage and may recycle about of 30% of N excreted (ca. 30 kg N $y^{-1}$) with small investment in infrastructure. Results from experimental work showed that covering manure heaps with a polythene film reduced mass and N losses considerably. For the poor farmers to increase overall NCE, investment in cattle housing and recycling of urinary−N is required (Chapter 3).

Table 1: Simulated feed intake, milk production and manure excreted by a dairy cow fed different diets based on Napier grass, supplemented seasonally with maize stover (ms) and dairy concentrate supplemented during lactation. Results show averages per year of lifetime and standard deviations.

| Diet | Forage DM intake (kg $TLU^{-1}$ $y^{-1}$) | Concentrates DM intake (kg $TLU^{-1}$ $y^{-1}$) | Milk production (kg $lactation^{-1}$ $TLU^{1}$) | Faecal DM (kg $TLU^{-1}$ $y^{-1}$) | Faecal N (kg $TLU^{-1}$ $y^{-1}$) | Urine N (kg $TLU^{-1}$ $y^{-1}$) |
|---|---|---|---|---|---|---|
| Napier grass | 2704 ± 458 | 0 | 2509 ± 361 | 1230 ± 205 | 12.6 ± 2.0 | 11.0 ± 1.4 |
| Napier grass +maize stover (ms) | 2054 ± 406 | 0 | 2043 ± 235 | 937 ± 168 | 9.3 ± 1.7 | 8.5 ± 1.2 |
| Napier grass+ms +2 kg concentrates | 2303 ± 426 | 237 ± 128 | 3094 ± 409 | 1090 ± 202 | 11.8 ± 2.2 | 9.9 ± 1.5 |
| Napier grass +ms +5 kg concentrates | 2788 ± 453 | 607 ± 168 | 3537 ± 471 | 1392 ± 205 | 16.7 ± 2.9 | 13.3 ± 1.8 |

Another experiment conducted in western Kenya (Tittonell et al., 2008a) to compare current and alternative manure storages, showed that storage in pits conserved more C and less nutrients than heaping the manure under a roof. Giving the relatively small amounts of manure available per farm, different strategies may fit different purposes. Conserving carbon (C) would be sensible if fertilisers are available to be applied in combination with manure composted in a pit. To save labour, manure composted in a roofed heap for a relatively short period (no more than 3 months, cf. Fig. 5 in Chapter 3), would give the best quality and the best response from the crops. When the amounts of manure available are very small, avoiding losses during composting may be the best strategy, which can be put into practice by manuring different fields with small amounts partitioned throughout the season. At the larger scale, there is concentration of nutrients and C through animal feed imported into the dairy farms from all surrounding farms that participate on the feed market, and from communal grazing. This may be partly compensated by the existence of a market for manure. Moll et al. (2007) estimated that manures represent about 6% of the income in an average dairy farm from Nakuru, in the Rift Valley province in Kenya. However, this will most likely not suffice to compensate for losses of organic matter from the fields of specialised feed producers.

There is not one simple recipe to successful crop-livestock integration as this depends largely on the farmer's own objectives, which are sensitive to fluctuations in the socio-economic environment. Enterprises that are successful today may drop in productivity in a relatively short time because of lack of external inputs and loss of (animal) capital. Intensifying crop-livestock system requires skilled farmers, and technical assistance (Waithaka et al., 2007), that may limit considerably the success of promising technical interventions. If livestock is to fulfil several functions, the design of interventions must consider farmers' demands to increase the likelihood of adoption and impact. Investing in highly productive animals makes it more difficult to decide to sell the animals when there is a need for cash.

## 2. Constraints at different scales: the use of modelling to explore options

Technologies that are designed to meet farmers' demands need to fit realistically with farmers' resources and constraints (IAC, 2004). The rehabilitation of soils only through the use of animal manure is unlikely to happen if feed availability limits what livestock can harvest and process. There is a wealth of research dealing with problems of poor soil fertility at plot scale in southern Africa, and particularly for the communal areas of Zimbabwe. Several technical solutions have been proposed since the early 1920's (see Wolmer and Scoones, 2000), most of them around the idea that mixed crop-livestock integration will increase the productivity of the land. Experimental work in the 1960 and 1970's indicated that large additions (10−40 t dry matter $ha^{-1}$) of animal manure were needed to support crop production (e.g. Grant, 1967; Rodel and Hopley, 1973), and based on those recommendation more recent research has assessed combinations of manure and other organic amendments with fertilisers (Giller et al., 1998; Mugwira et al., 2002; Mtambanengwe et al., 2006). Although the results of plot scale trials, especially those with applications of legumes or other organic resources in combination with fertilisers show promise for increasing crop yields, animal manure in combination with fertilisers usually gives the best results. This is most probably due to the addition of other nutrients (e.g. Ca, Zn) than N and P with the manures (Zingore et al., 2008) thereby preventing acidification of soils in the long term (Grant, 1967).

Heterogeneity within farms due mainly to differential management of organic resources has been observed in the communal farming areas of Zimbabwe (Chibudu et al., 2001; Mtambanengwe and Mapfumo, 2005; Zingore et al., 2007b). Farmers manage the soils of their farm creating 'islands of fertility' or 'hotspots' from which good yields are obtained. This phenomenon is also commonly observed in mixed farming systems in West Africa (De Ridder et al., 2004; Ramisch, 2005; Breman et al., 2008). A prerequisite for this strategy to be effective is the availability of organic resources to be fed to livestock or to practice mulching. Ideas on land planning from the colonial time persist until now in Zimbabwe. Barnes (1978) discussed the need of stimulating intensive profit-oriented farming in communal areas (Tribal Trust lands), for which the major constraint was the collective management and decisions made at the community level. He suggested, as an alternative to comply with the tribal customs, the allocation of a piece of arable land to each family, and a delimited grazing land divided into paddocks to the whole community, and the unification of the herd of the village. This type of (collective) management was observed in our study site in NE Zimbabwe (Chapter 7).

We explored the consequences of competition for use of organic resources on the productivity of different farm types within a village area in Zimbabwe (Chapter 7). The analysis was focused on village scale recognising that this is the relevant scale where the constraints to sustaining cropland productivity with animal manure are defined. The village was a virtual village in which a number of key features of the real village are represented: the ratio between grassland and cropland, the size of the actual collectively-managed herd, different farm types with different field types, their resources (livestock, labour force and access to input), and differential resource allocation within the farm types. Different management options were explored for the different farm types. A temporal scale of ten years was used to evaluate dynamically 'what if' trajectories, although rather statically in the sense that the farms did not evolve into different types, and adaptive management did not take place. This analysis was meant to explore the magnitude of the interactions, and how collective change may modify collective outcomes. The explorations suggested that the current use of the biophysical resources leads to more inequity in the village, by an uneven concentration of soil fertility among different farm types in the community. In practice, there is more diversity as interactions within a community not only involve biophysical resources but other social relations

(Fairhead and Leach, 2005), such as exchanges of labour, manure, grain, within extended families and between households, that at least partly compensate for the nutrient losses and lower yields of some poorer farmers within the community. For instance, Dekker (2004) identified the lack of oxen to plough as one the main six risks that affect the livelihoods of small scale farmers in communal areas of Zimbabwe, and the main risk-coping strategy was the support network within the community.

The model explorations were useful to test hypotheses, and to generate new questions. It takes a long time to observe the benefits of improving soil organic matter, especially with the relatively small amounts of biomass and manure available in the farming systems under study, and where there are competitive uses of the organic resources. Effects of different management of the organic resources on yields from poor soils may not be perceived in one or two seasons, which may discourage farmers from testing alternative technologies. Combining these with fertilisers, may pave the way to gain interest from potential users. The role of livestock in accelerating this process is important, but will not be enough to substitute for the need for external inputs to start the restoration of soil fertility when more land is needed for food production. The applicability of the management options identified requires farm scale evaluations, which may be model-assisted. We plan in the near future to combine participatory approaches that will allow targeting our research on integrated soil fertility management to the needs of the farmers, within the boundaries imposed by collective management. Options need to be analysed within the diversity of existing management strategies, and to test the applicability of the options identified within this modelling research, the combination of experimentation and farmers views is needed.

## 3. Modelling approaches and their role in farming system analysis

At the start of the NUANCES (Nutrient Use in ANimal and Cropping systems–Efficiency and Scales) project in 2001 (Giller et al., 2006), the expectations were to be able to summarise existing knowledge and explore options within diverse farming systems, targeting the farm scale, where management decisions are taken, by using modelling techniques. The ambitions were to use existing databases, characterise farming systems from selected study sites, to use existing models and to develop simple models when there was an important gap, and a justified need for investing in model development according to farming system-specific research questions.

This research was central to the development of the analytical framework (see specific objective 1 in Chapter 1). The modelling tools were used to explore hypotheses on systems functioning, while accepting that some gaps in knowledge may lead to (over) simplifications of key system processes (Schlecht and Hiernaux, 2004). Yet, the use of these techniques has led us to make choices on the basis of the relative importance of detail and complexity to the research questions and to stop when the current knowledge was insufficient to Describe, Explore, Explain and Design. The models included in NUANCES-FARMSIM (see Tittonell et al., 2005a; Rufino et al., 2007a; Rufino et al., 2007b; Tittonell et al., 2007; Van Wijk et al., 2008), are all based on accepted principles, from which key aspects were modified to fit the exploration needs. The first stage of the development of the framework has focused on the exploration of feasible biophysical options for intensification in crop-livestock farming system at different scales: crop (e.g. Tittonell et al., 2008b) and livestock sub-systems (Chapter 4), organic resources and manure management sub-system (Chapter 3), farm scale (Tittonell et al., 2008c) and village scale (Chapter 7). After three years of iterative cycles of model development, calibration, testing and re-design, we understand that is extremely difficult to generate tools that may be used to draw conclusions on interventions that will be appropriate under all conditions, because always understanding on the farming system functioning is needed. The model-assisted explorations were built on large amounts of previous research at each of the sites where the studies were carried out, complemented with new experiments and field observation especially addressed to characterise management. It is possible to use the tools for model exploration and test hypotheses in other locations than western and central Kenya and communal farming in Zimbabwe, but the adaptation, calibration and testing of the models will not be a trivial task.

However, systems analysis and the modelling framework have been very useful to stimulate fruitful discussions among researchers and have helped to identify critical gaps in the current knowledge of biophysical processes that are relevant to address properly future research needs. For example, the plant-animal interactions in grazing modelling (Illius and Hodgson, 1996), which is based on foraging theory (Stephens and Krebs, 1986), is an area that requires more research especially to understand the exploitation of heterogeneous natural vegetation by the herds (Scoones, 1995; Turner et al., 2005), and adaptation in case of climate stress. Another area that needs more research, is the identification of options for rehabilitation of inherently poor and/or degraded soils, and the long term responses to those interventions. We plan to address some of these issues in our future research agenda. Our expectation at the beginning of this research was to use the tools together with the characterisation of the sites included in the AfricaNUANCES project, to address specific questions at each of the sites. Unfortunately the data collection and processing is not yet complete in all eight sites (see www.africanuances.nl), which means that the process of Describe, Explain, Explore and Design is far from finished. Furthermore, the usefulness of models in highly complex farming systems is debatable. Farmers are adaptable and individual systems change over time. The current limitation of models to capture these dynamics properly means that they can help in assessing management options, but will not give complete answers.

In brief, modelling was useful for summarising existing information, to identify and (when possible) fill gaps in knowledge, and also to define at which scale the alternative for current problems need to be explored. There are other modelling approaches, such as multi-agent modelling that show some promise to analysing complex and diverse systems. Thornton et al (2007) suggested that this technique may be useful to incorporate in a more dynamic fashion the evolution of the farm households. Schlecht and Hiernaux (2004) propose its use to model dynamically management decisions. Multi-agent modelling, developed in the world of artificial intelligence, may be useful to address questions related to human relations and resource use at different scales (human-environment interactions). A 'multi-agent model of land use change' is a combination of a cellular landscape model with agent-based representations of decision making that integrates interdependencies and feedbacks between agents and the environment (Parker et al., 2003). The cellular model represents biophysical and ecological aspects of the system (the environment in which agents act) and the agent-based model represents the human decision making about the environment. Rouchier et al. (2001) developed a multi-agent model to explore the relationship between nomad herdsmen and farmers in N Cameroon. The simulations showed an emerging pattern (regular dynamics) on resource use, which is based on the social agreements and a learning process for the agents. Building a multi-agent model requires a great deal of understanding on how the system under study works, and it does not prevent a large number of assumptions and simplifications on how agents make decisions. Although it offers opportunities for incorporating dynamics in the decision making, and keep diversity and heterogeneity within communities, outcomes should be compared with what simpler dynamic modelling techniques and the use of rule-based methods have to offer. Both approaches have a potential use that need to be further explored, and it is the role of modelling in accompanying process of change (companion modelling) (Bousquet et al., 2007). Experiences in northern Thailand, indicated that the process of building the multi-agent model, the exploration, and playing games with the farmers, changed the whole perception of what the problems were for the researchers and also for all the stakeholders who acquired a richer view of each others realities (Bousquet, F. 2006, Pers. commun.). It was the process of building models that was the most useful instead of the models themselves. In general, models may be an useful instrument to stimulate discuss, particularly when the stakeholders views are consulted at early stages in the model development process and when the recognition of a need for changes is shared (Sterk et al., 2006).

## 4. Risk, vulnerability and adaptability in crop-livestock systems

Risk is an important component of smallholders farmers' livelihoods (Dercon, 2005). Common sources of risks are for example droughts, pests and diseases, market shocks and political instability. Households are more exposed to risk (i.e. are more vulnerable), when they are poorly endowed and are poorly supported or excluded from social networks. The frequency of occurrence of droughts has increased in last twenty years in Zimbabwe (Matarira et al., 2004) and this may increase further due to the effects of climate change. Droughts have a clear short term effect on food production, exposing everybody within a community to risk. The long term consequences are due to destocking used as a risk coping strategy, which does not completely insure families, or due to massive death of cattle. In times of drought the value of animal products drops down and the capacity of livestock to smooth consumption becomes limited (Fafchamps et al., 1998). Instead farmers often may choose to reduce consumption and preserve livestock, an strategy that appears to have large consequences for children (Hoddinott, 2006). Example of the long term consequences of drought is the poor recovery of the cattle population in Zimbabwe after the droughts of 1991–92 (Chibudu et al., 2001). During model explorations, we observed that the size herd of our virtual village (Chapter 7), would be reduced by about 60% after the two consecutive droughts and that there was no recovery within the simulation period under the baseline mortality rates. Restocking is extremely difficult for smallholders, because of their limited capacity to accumulate cash to reinvest in cattle and because the surplus production of crops is also erratic in these environments (see Chapter 7). The introduction of small ruminants helps accumulating asset and provides opportunities for restocking, besides small ruminants represent small cash for farmers. In the future a module for simulating the production of small ruminants will be included into FARMSIM. Diseases also prevent the quick recovery of the herd populations, so interventions that will be addressed to improve health of livestock may have an important impact on whole communities and reduce their vulnerability to risk. The complexity of these relationships and their dynamics can be explored with FARMSIM and the impact of alternative management can be analysed through scenarios. Climate change can increase the effect of thermal stress on livestock productivity, conception rates and health of livestock, potentially more in exotic (*Bos taurus*) or cross bred cattle kept for small-scale dairy production in the tropics (King et al., 2006). These relationships may be incorporated into LIVSIM for future exploration of the effects of climate change in combination with other interventions strategies as mentioned in Chapter 4.

In principle, in zero-grazing systems feed supply is kept more constant than in grazing systems. However seasonal feed availability and quality still follows the rainfall patterns thereby resulting in contrasting body weight changes during the rainy and the dry season. Milk and manure production usually follows this seasonality. Although technologies have been developed to overcome feed deficits (in quantity and quality) during dry periods, farmers do not adopt these technologies. In this way they do not achieve the expected productivities of the breeds for the given environment (Chapter 4). The poor adoption of the technologies (e.g. fodder conservation), may have different reasons, but the most common is that technologies do not fit farmers needs and possibilities. This appears to be the reason of limited success in the adoption of fodder legumes (Sumberg, 2002b; Sumberg, 2004).

Within smallholder communities, not even the wealthier smallholder farmers are resource use efficient although there is a pressure for more production and cash generation. From poor to wealthier farmers there is some risk spreading strategy that leads to low resource efficiencies. So, whether resource use efficiency is a good indicator is debatable. This point of discussion needs to be included in our assessments of system performance at farm and higher scale because farmers do not always maximise utilities, nor pursue economies of scale (Moll et al., 2007). Urgent needs governed by tactical decision making may overrule farmers strategic plans. Labour intensive technologies to improve productivity and conserve nutrients through (animal and green) manure management, can be unattractive considering the time horizon of farmers' decision making. Adaptability is key to reduce vulnerability to risk.

Ecology regards mature ecosystems as characterised by organised patterns of material and energy flows, intense recycling, and relatively little dependence from the exterior environment (Odum, 1969). Their resilience is sustained on a structure that supports a diversity of flow paths that allows buffering of external shocks. Agro-ecosystems have in contrast to fulfil the goals (and aspirations) of the farmers, for which they need to be productive, reliable, (production should be stable or increase), and adaptable to match (opportunistic) decision making. Smallholder crop-livestock systems are diverse, often adaptable and risk-spreading by nature. And this may lead to apparent resource use inefficiencies. The use of network analysis using nutrient or other currency to account for resource allocation and configuration of the farm household system appears promising to assess these system properties: productivity, reliability and adaptability, by looking at dependency on the external environment for biophysical inputs and the internal organisation of the system (Chapters 5 and 6). Results indicate that increases in size of the network of N flows and organisation of the flows lead to increases in productivity and food self-sufficiency and also reduce dependency. Combination of both strategies may benefit not only productivity but also adaptability and reliability of smallholders crop-livestock systems.

We made a first step in testing these hypotheses, and plan to include more similar and contrasting systems that were observed once in time (e.g. De Jager et al., 2004; Gachimbi et al., 2005), but also farm systems that have been observed for a number of years (Ousmane et al., 2008). Analyses such as network analysis (NA) that can be used for system (re)design can by introducing qualitative and quantitative changes into a farming system increase their productivity, as far as the inflow of the external force is sustained, but may lead to new configuration with unexpected consequences when the system is left to be driven by itself. Schiere et al. (1999) discussed the need of more conservationist farming system research approaches to shape agricultural development according to resource availability. We should be asking ourselves these questions, to consider which trajectories of change we may want to explore, looking at past transformations may provide some insight (De Ridder et al., 2004; Van Keulen and Schiere, 2004).

## 5. A way forward: new opportunities for intensification?

Integration of crop-livestock may increase the productivity of individual farms provided that: competition for (natural) resources does not become critically high and degradation induces abandonment of farming. There are benefits in terms of productivity and resource use efficiency of closer integration between crops and livestock. Some of these benefits can be obtained with relatively small technical changes. Others need to be combined with radical institutional changes and/or system shifts. Targeting feeding according to the physiological needs of the dairy cows can increase productivity of dairy systems without large investments. Increasing milk production of traditional breeds through supplementation of relatively small amounts of fodder legumes may not generate a considerable amount of income to the household, but may improve considerably the protein intake of the children (Randolph et al., 2007). Introducing exotic breeds to places where feed availability and access to veterinary service and inputs are not guaranteed, may lead to discouraging the adoption of other more suited technologies. Reduction of mortality rates will require institutional interventions, which are justifiable considering the expected benefits for smallholders.

Changes in manure management, which require small investments such as covering manure heaps, will have long term effects on crop production, especially where farmers cannot afford purchasing mineral fertilisers. Nutrient cycling and conservation of nutrients from animal manures, through reducing the number of steps from excretion to application to the land is an option to explore. Incorporating manures into the soil at shorter intervals is an option when labour demands from other activities are not critical. Intensification is not only limited by the size (and management) of the common resources but by the social agreements between (key) members of the community. Social networks play an important role in the dynamics and opportunities for improvement of the farming system, and options needs to be discussed within the communities that we may want to target. Modelling has a role in this process of exploring feasible futures, but we will be closer to make a contribution to intensification and to poverty reduction when we are able to understand *farmers' models*.

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# Appendices

# Appendix 1: NUANCES – LIVSIM: the Livestock Simulator†

## 1. Overview and conceptual approach

The Livestock Simulator (LIVSIM) is the animal production module of the NUANCES modelling framework (Fig. A1). LIVSIM is a simple dynamic model based on principles of production ecology (Van de Ven et al., 2003). There is a hierarchy of production factors that determine whether potential, limited or reduced yields are attained (Fig. A2). Defining factors are the animal genetic characteristics and climate. Potential production is achieved if feed and water requirements are satisfied. Water and feed intake are the limiting factors. Disease, pollutants and other factors related to well-being of the animals are the reducing factors. LIVSIM simulates individuals that have to be aggregated to represent different animal sub-systems: dairy, animal traction, mixed herds for beef production or fattening sub-systems. Management decisions related to feeding and breeding are incorporated into LIVSIM but marketing and culling decisions are derived from household strategies, goals and production orientation and are included in the core model FARMSIM. Individual animals are followed in time, and performance depends on genetic potential and feed resources. Genetic potential is described in the model by maximum mature weight, potential growth rate and maximum milk yield. Fig. A3 shows the structure of the model.

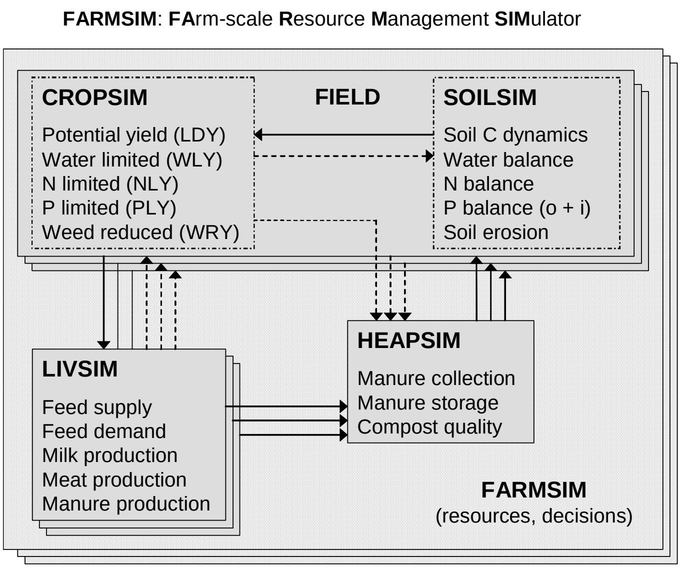


Figure A1. A schematic representation of NUANCES-FARMSIM, the farm-scale modelling shell linking soil, crop, livestock and manure models and accounting for availability of farm-scale resources (such as cash and labour) and their dynamics throughout the year.

† Adapted from:
Rufino, M.C., M. Herrero, M.T. Van Wijk, J. Dury, N. De Ridder and K.E. Giller. 2007. NUANCES – LIVSIM: The Livestock Simulator. AfricaNUANCES Working Document 6. Plant Production Systems Group, Wageningen University Wageningen, The Netherlands. Available at http://www.africanuances.nl

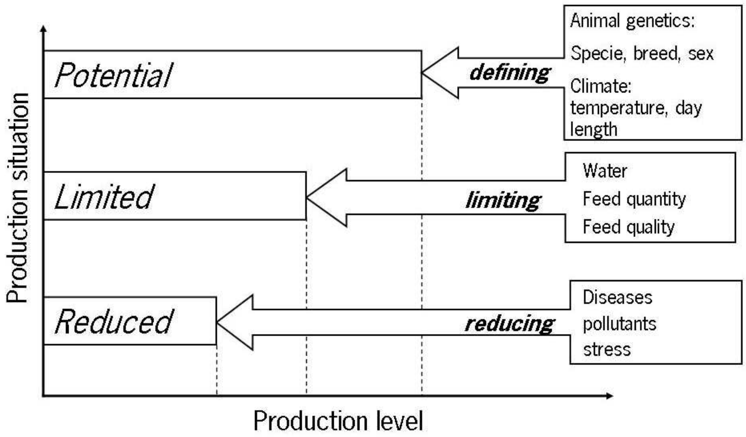


Figure A2: Animal production situations and production levels as determined by production defining, limiting and reducing factors. Source: Van de Ven et al. (2003).

The nutritive requirements are calculated for individual animals, on the basis of requirements for growth, reproduction (requirements for gestation) and production of milk. The current version of LIVSIM is developed to simulate cattle production. Conception, sex of the calves and mortality (involuntary disposal) are triggered stochastically while changes in age, weight and mortality due to under-nutrition are described deterministically. Intake is driven by feed quality and animal characteristics. Decision variables represent different management strategies related to feeding (quantity and quality), breeding policies. Reproductive performance can be evaluated through a number of indicators: age at first conception, days open, calving interval and length of the productive life (culling date minus first calving date). Productivity can be assessed with number of calves, milk production, weight gain and manure production. The model is written in MATLAB v.7.0.4 (The Math Works, 2005), the integration time-step is 30 days. The basic structure of the model is based on the concepts of the model developed by Konandreas and Anderson (1982). LIVSIM differs from that model in the nutritive requirement calculations − which are based on metabolisable energy (ME) and protein systems of AFRC (1993), feed intake − based on the model of Conrad et al. (1966), excreta production, and the decision making variables. Individual components of the model were tested against experimental data obtained from literature and are presented in the model evaluation section.

## 2. Model purposes and structure

LIVSIM is designed to simulate the impact of different management strategies on the long-term productivity of cattle. The main objective is to quantify dynamically the production of milk, manure and offspring of individual animals of small herds common in smallholder farming systems in Sub-Saharan Africa. The purpose of such an analysis is to identify options for optimising the use of farm resources instead of the maximisation of one single production trait. The cattle model may be linked to FARMSIM for the allocation of nutrients, labour and cash resources and allow farm-scale exploration of different livelihood strategies. Individual animals are described with four state variables: age, bodyweight, the reproductive status comprising a pregnancy index and a calving index (Fig. A4). The pregnancy index is used to follow in time the pregnancy and its nutritive requirements and to trigger calving. The calving index is used to follow the lactation and its nutritive requirements in time and for triggering the next conception.

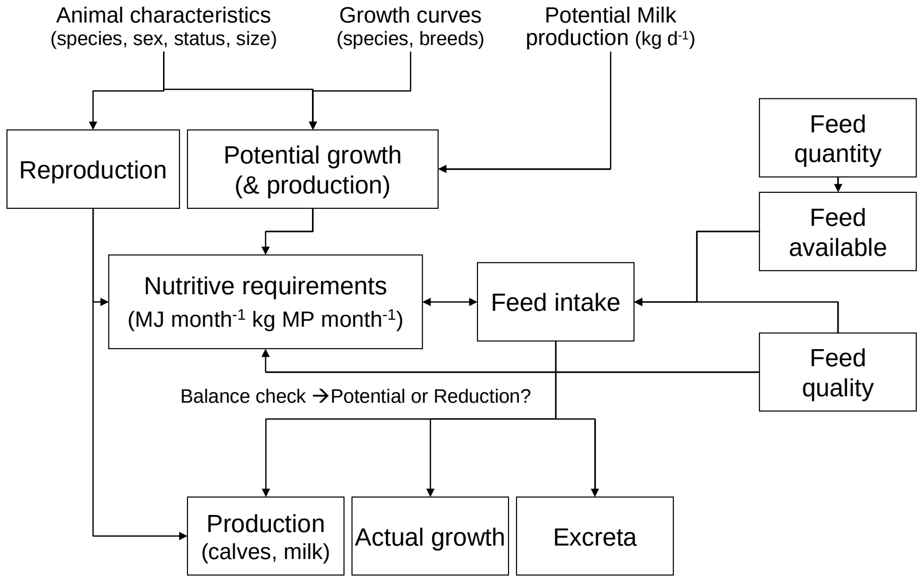


Figure A3: Simplified scheme of LIVSIM-cattle, where the boxes represent the different modules of the model where nutritive requirements of different for different physiological processes are compared to the actual intake of energy and protein available. MP stands for metabolisable protein.

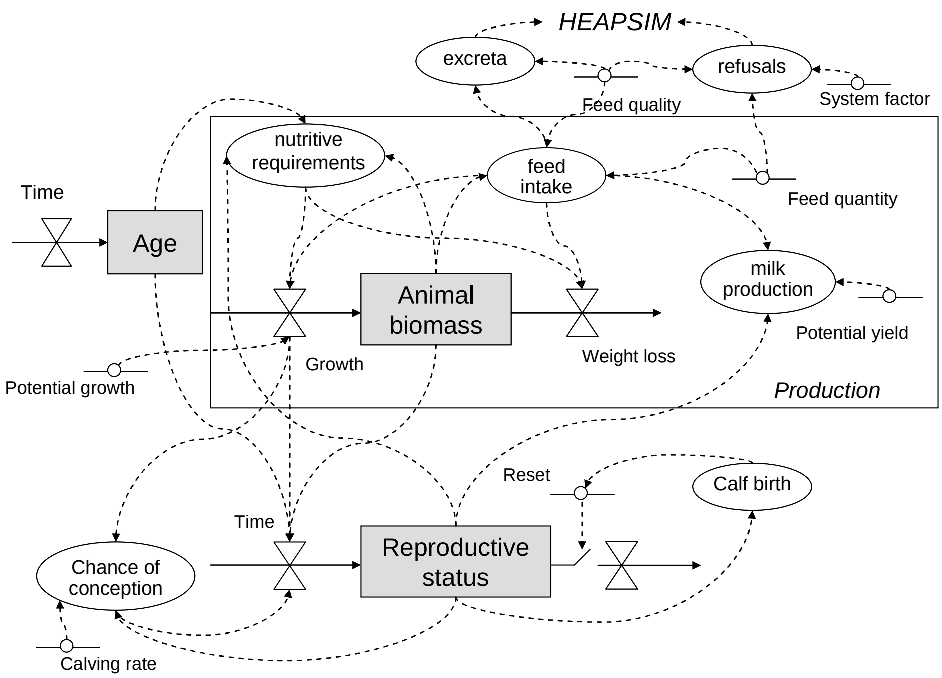


Figure A4: States and rates variables diagram of LIVSIM-cattle. System factor is a parameter that indicates the proportion of wastage of feed by the animals.

## 2.1 Growth and compensatory growth

Potential growth is a function of age, breed and sex. Potential growth and minimum bodyweight curves are built for a cattle breed fitting data on mature weight and growth rates found in the literature to a simplified Brody model (Brody, 1945). The potential growth curve for female cross-bred HolsteinFriesian × Zebu is shown in Fig. A5.

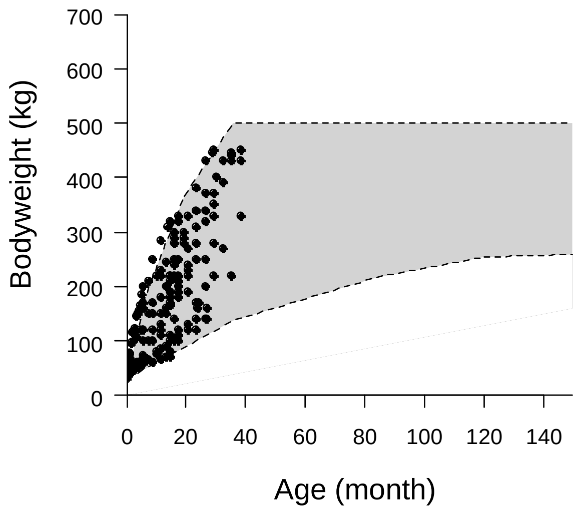


Figure A5: Potential growth curve for cross-bred Holstein-Friesian female × Zebu cows growing in the tropics. After Lanyasunya et al. (2000), Agyemang and Nkhonjera (1986) and Konandreas et al. (1983).

Maximum and minimum bodyweights are calculated by interpolation from the upper and lower boundaries shown in Fig. A5. Next, the difference (Difference Max W) between actual weight ($W_t$) to maximum weight (W max) is calculated according to:

$$Difference\ \ Max\ \ W = W_{\max,t+1} - W_t \qquad \text{(Eq. 1)}$$

Compensatory growth is accounted for in the model by using different potential growth rates (Table A1) according to quality of the feed (Tolkamp and Ketelaars, 1994). For each diet quality, it is determined which is the maximum growth rate according to the metabolisability of the feed (qm).

Table A1: Daily weight gain rate according to metabolisability of the feed (qm). After Tolkamp and Ketelaars (1994).

| | Average Daily Weight Gain (kg d$^{-1}$) | |
|---|---|---|
| qm (MJ MJ$^{-1}$) | females | males |
| 0.2 | 0.3 | – |
| 0.3 | 0.5 | 0.5 |
| 0.4 | 0.5 | 1.0 |
| 0.5 | 1.0 | 1.5 |
| 0.6 | 1.5 | 2.0 |
| 0.7 | 2.0 | 2.5 |

The actual growth per month is calculated as:

$$Actual\ Growth_{t+1} = \min\left(AWG, Difference\ Max\ W\right) \qquad \text{Eq. 2}$$

Where Actual Growth is the minimum of Difference Max W and the maximum growth allowed by the metabolisability of the feed (AWG) expressed in kg per month.

## 2.2 Reproduction

Reproduction is simulated stochastically by using probabilities associated to bodyweight and age combinations. We used the approach of Konandreas and Anderson (1982) and data from the literature to determine a feasible age-bodyweight set when heifers achieve reproductive maturity (Fig. A6). The minimum (1.5 y), average (2.2 y) and maximum (4 y) ages for conception were derived from the minimum age at first calving from 12 studies with grade and cross bred Holstein-Friesian × Zebu cattle in Sub-Saharan Africa. Probabilities for conception are derived from the annual calving rate (input to the model), this probability is a function of age (Table 2). The nutrition-reproduction feedback is described through the effect of bodyweight changes in the annual conception rate. We used the experimental work of Richardson et al. (1975) to describe this relationship (Fig. A7). Because cows reach their maximum fertility around the middle of their reproductive life a multiplier to take into account the effect of age on the annual calving rate is used (Table A2).

Table A2: Multiplicative effect of age on the annual conception rate of cows After Konandreas and Anderson (1982).

| Age (y) | Multiplier for the effect of age on calving rate |
|---|---|
| 1.5 | 0.75 |
| 3.5 | 1 |
| 8 | 1 |
| 12+ | 0.625 |

The monthly probability of conception is calculated in Eq. 3. Calving rates and conception rates are assumed to be equal.

$$Prob\ Conception = 1 - \left(1 - Annual\ CalvingRate\right)^{1/12} \qquad \text{Eq. 3}$$

This probability of conception is further affected by postpartum length and management (presence of bull or artificial insemination). Postpartum length is assumed to be 2 months, where RF postpartum equals 0, otherwise equals 1. When bull or artificial insemination is present RFbull equals 1, otherwise 0. The adjusted probability of conception accounting for all factors is finally calculated as:

$$Monthly\ Prob\ Conception = Prob\ Conception \times RF\ \ postpartum \times RFbull \qquad \text{Eq. 4}$$

The adjusted monthly probability of conception (Eq. 4) is compared with a random number drawn to determine whether a heifer or a cow conceive during the time step. The reproductive status of females is followed by using 2 indices: "pregnancy index" that keeps track of the evolution of the pregnancy and a "calf index", which indicates when the calf is born. Both indices are reset when a new calf is born. A distinction between heifers and cows is made. Heifers have to fulfil age and bodyweight requirements to conceive. Gestation lasts 282 days, which is within the reported range of 270−292 days (Mukasa-Mugerwa, 1989). New calves are assumed to be born with a user-defined initial weight and gender is assigned using a random number.

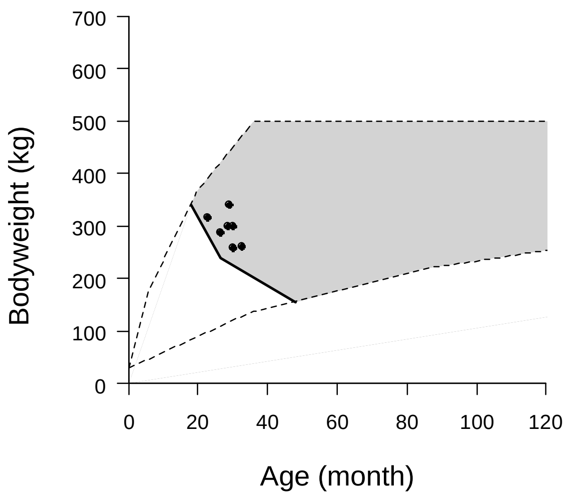


Figure A6: Feasible set of bodyweight-age combinations for conception of grade and cross-bred Holstein × Zebu in SSA. After: Trail and Marples, 1968; Knudsen and Sohael, 1970; Kabuga and Agyemang, 1984; Agyemang and Nkhonjera, 1986; Staal et al., 2001; Waithaka et al., 2002; Bebe, 2003; Masama et al., 2003; Jenet et al., 2004a; Ngongoni et al., 2006; Ongadi et al., 2007.

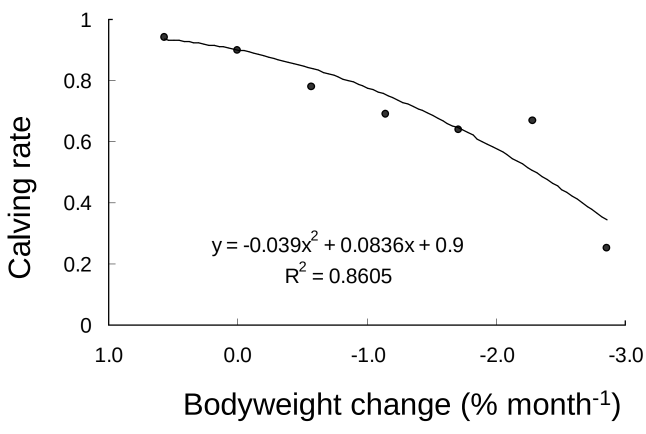


Figure A7: The effect of bodyweight changes on the calving rate of female cows. Source Richardson et al. (1975).

## 2.3 Milk production

Milk yields are simulated by using a breed-specific potential milk yield function of lactation length (Fig. A8), modified by age and condition of the cow (Table A4). Lactation length and dry period are characteristics of the system and therefore inputs to the model. The dry period is assumed to be 2 months. Milk production (Eq. 6) is calculated by using interpolation using the potential lactation curve and correcting by age and body condition effects (Tables A3 and A4).

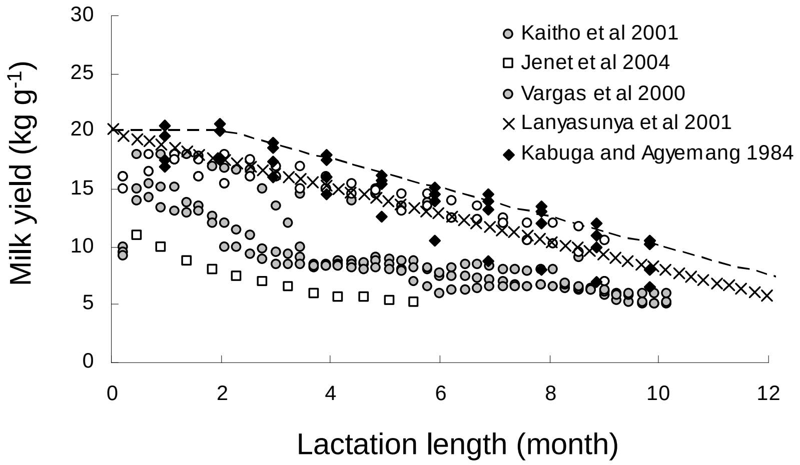


Figure A8: Lactation curves for cross bred Holstein-Friesian × Zebu cows in SSA. The dotted line is the simplified potential lactation curve used in LIVSIM. Sources of the data are indicated in the figure legend.

Table A3: Effect of age on milk production. Data source: Konandreas and Anderson (1982).

| Age (y) | Fraction of maximum yield |
|---|---|
| 2 | 0.8 |
| 3 | 0.8 |
| 5 | 1 |
| 8 | 1 |
| 12+ | 0.6 |

The condition index is calculated as:

$$Condition\ Index = \frac{W_t - W_{\min,t}}{W_{\max,t} - W_{\min,t}} \qquad \text{Eq. 5}$$

Table A4: Effect of body condition on relative milk production. Data source: Konandreas and Anderson (1982).

| Condition index | Condition factor |
|---|---|
| 0 | 0 |
| 0.3 | 1 |
| 1 | 1 |

The attainable milk yield is calculated as:

$$Milk\ Yield = Potential\ Milk\ Yield \times Age\ Effect \times Condition\ Factor \qquad \text{Eq. 6}$$

The energy and protein requirements for milk production have to be met by the intake of energy and protein. When feed intake does not meet the needs for potential production, the actual milk yield is calculated by iteration accounting for all the processes demanding energy and protein and using a set of rules explained in Section 2.6. Weaning age and milk allowance for calves is a characteristic of the system and therefore user-defined. For the intensive dairy systems of Central Kenya milk allowance was set to 4 L of milk $d^{-1}$ when the calves are born up to 0.5 L $d^{-1}$ when they are weaned at 3 months of age. Mortality rates due to causes other than under-nutrition (e.g. injuries, accidents, diseases, etc.) are input to the model. Mortality due to starvation is simulated by using the growth and reproduction routines.

## 2.4 Nutritive requirements

Nutritive requirements are calculated following the energy and protein system of AFRC (1993). Metabolisable energy (ME) and metabolisable protein (MP) requirements are calculated separately for maintenance, growth, pregnancy and lactation. This structure allows application of the concepts of production ecology (Van de Ven et al., 2003).

## 2.5 Feed intake

Accurate predictions of intake for modelling cattle performance are necessary because intake links the management of fodder resources to the animals. Evaluation of intake models has been the subject of a number of studies (e.g. Waldo, 1986; Ketelaars and Tolkamp, 1992b; Pittroff and Kothmann, 2001c; Pittroff and Kothmann, 2001b; Pittroff and Kothmann, 2001a; Coleman and Moore, 2003; Fuentes-Plia et al., 2003; Keady et al., 2004). There is agreement on the need to build standard databases of feed quality and animal performance that can be used to design equations to predict feed intake that consider variability in feed supply. However, accurate estimation of individual dry matter intake (DMI) in ruminants, especially in lactating cows, is difficult to achieve because of the many external (i.e., changes in weather, or in fibre content of the feed) and internal (i.e., DMI regulatory stimuli) factors affecting voluntary intake between and within days, causing day to day variation (Molina et al., 2004). Pittroff and Kothmann (2001a) questioned the usefulness of highly aggregated regression models because of the inelasticity of their response. Most intake models are empirical and designed to predict intake of cattle in a certain environment where they are useful for analysing management decisions. A drawback of simple intake prediction models is that they cannot be used to predict intake in conditions different from those used for the fitting of the data. The applicability of the model needs to be analysed for the system under study and this needs to be documented. In this section we show the results of testing a number of intake models (Table A5).

### *2.5.1 Intake prediction models*

A summary intake function was derived with the metabolic Ruminant model (Herrero, 1997). The model was run under the following conditions: Bodyweights between 0 to 500 kg, feed dry matter digestibilities between 45% to 65%, crude protein (CP) between 50 to 150 g (kg DM)$^{-1}$, neutral detergent fibre (NDF) between 500 and 800 g (kg DM)$^{-1}$. A factorial experiment was designed using these data, and with the results linear and non-linear regressions were performed. The best fit equation is presented in Table A5. The second model presented was developed by Ketelaars and Tolkamp (1991) for sheep and used in modelling cattle production in the tropics by Udo and Brouwer (1993) and Zemmelink et al. (2003). The third model proposed by Conrad et al. (1964; 1966) and adapted for use in the tropics by Kahn and Spedding (1984). The fourth model is the simplest approach used to formulate diets and it is widely accepted, it uses a fraction of the bodyweight to calculate the amount of feed to offer. Fractions generally used range from 2−3% BW but experimental work showed that the range can be as wide as 1.7−3.6% BW depending on the quality of the feed or 0.4−2.2%BW depending on the availability of the feed under grazing conditions (Lopes et al., 2004).

### *2.5.2 Testing of the intake models*

We selected from the literature a number of studies carried out in the tropics of Sub-Saharan Africa where quality of the diet, bodyweight (BW) and DMI for cross-bred cattle was reported (Table A6). We used the coefficient of determination ($r^2$) as a indicator of precision, slope and intercepts of the linear regression line as indicators of accuracy. To judge the overall model performance we used the mean square prediction error (MSPE) (Table A7). The performance of the Ruminant, Conrad and fraction of BW models is depicted in Fig. A9 for Azawak steers (Ayantunde et al., 2001), Fig. A10 for Holstein × Ayshire steers, (Delve et al., 2001) and Fig. A11 for lactating cross bred Holstein-Friesian × Zebu cows (see sources in Table A6). The evaluation of the intake models (Table A7) shows that there is no generic model of intake prediction and although the simplest model (a fraction of BW) appears to be the best, the fraction that fit the best changes for different physiological status. Probably there are also large differences between breeds. That is the reason why we chose Conrad’s model for lactating cows until we find a model that fits the data better with sound theoretical background. New models available can be tested at farm level by using the integrated analytical tool FARMSIM. The objective was to evaluate the degree of detail needed to capture the variability in input-outputs.

Table A5: Selected models for intake prediction. $DMI_f$ : dry matter intake of forages (kg $d^{-1}cow^{-1}$), BW: bodyweight (kg), $DMD_f$: dry matter digestibility of the forages (g kg $DM^{-1}$), $CP_f$: crude protein content of the forage (g kg $DM^{-1}$), $NDF_f$ : neutral detergent fibre content of the forages (g kg $DM^{-1}$), $DMI_c$ :dry matter intake of concentrates in kg per day, $NDF_c$: neutral detergent fibre content of the concentrate (g kg $DM^{-1}$) and $CP_c$ is crude protein content of the concentrate (g kg $DM^{-1}$).

| Ruminant type | Equation | Location | Reference |
|---|---|---|---|
| Dairy cows | $DMI_f=0.016\times BW+0.81\times DMD_f+0.009\times CP_f-0.002\times NDF_f-0.225\times DMI_c-0.002\times NDF_c-0.004\times CP_c$ | Tropics | Herrero (1997) |
| Sheep | $IOM_f=(-42.78+2.3039\times OMD_f-0.0175\times OMD_f^{\ 2}-1.8872\times N^2+0.2242* OMD_f \times N)\times 1.33$ | Tropics | Ketelaars and Tolkamp (1991) |
| Dairy cows | if $DMD_f<0.67$ $DMI_f=0.0107\times BW/(1-DMD_f)$ | Temperate conditions | Conrad (1966), Kahn and Spedding (1984) |
| | otherwise $DMI_f$=ME for maintenance, growth and production/ME content feed | | |
| Generic | $DMI_f=fraction\times BW$ | | |

Table A6: Studies selected for testing different model of intake prediction.

| Cattle type | Breed | BW | Diet | Location | Reference |
|---|---|---|---|---|---|
| Steers | Azawak | 367±76 | Grassland annual grasses | Niger | Ayantunde et al (2001) |
| Steers | Holstein-Ayshire | 246±26 | Barley stover + legumes or poultry waste | Kenya | Delve et al (2001) |
| Heifers | Holstein | 180±9 | Napier grass + legumes | Kenya | Kariuki et al (1999) |
| Dairy cows | Holstein | 377±43 | Napier grass + legumes or concentrates | Kenya | Nyambati et al (2003) |
| Dairy cows | Holstein | 439±39 | Napier grass + concentrates or poultry waste | Kenya | Muia et al. (2000) |
| Dairy cows | Ayshire x Sahiwal | 384±41 | Napier grass + legumes | Kenya | Muinga et al. (1995) |
| Dairy cows | Holstein x Boran | 297±36 | Rhodes grass + concentrates | Ethiopia | Jenet et al. (2004b) |
| Dairy cows | Holstein and Ayrshire | 433±11 | Maize stover + concentrates | Kenya | Methu et al. (2001) |

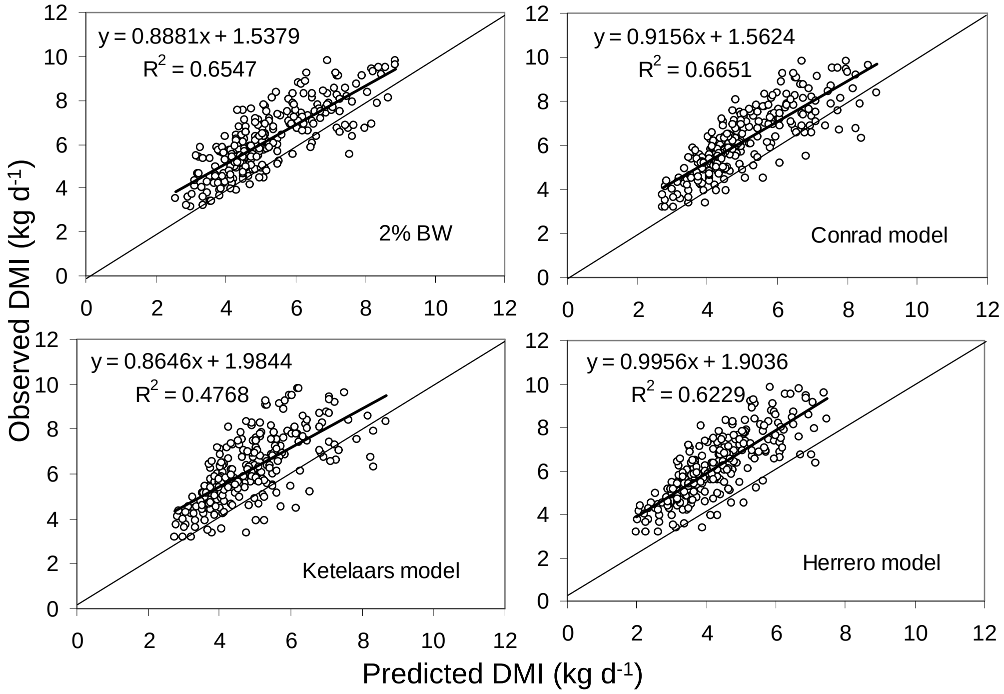


Figure A9: Observed DMI for Azawak steers plotted against predicted DMI using the Ruminant model of Herrero (1997), the Conrad model (Conrad, 1961; 1966), the model of Ketelaar and Tolkamp (1991) and the fraction of BW model.

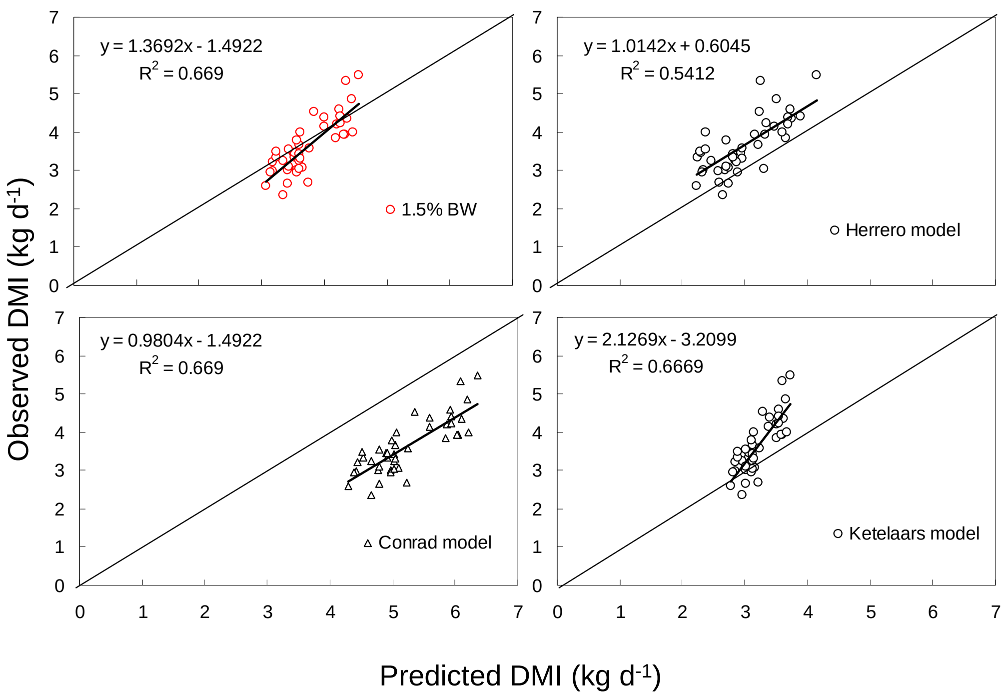


Figure A10: Observed DMI Holstein × Ayshire steers plotted against predicted DMI using the Ruminant model of Herrero (1997), the Conrad model (Conrad, 1961;1966), the model of Ketelaar and Tolkamp (1991) and the fraction of BW model.

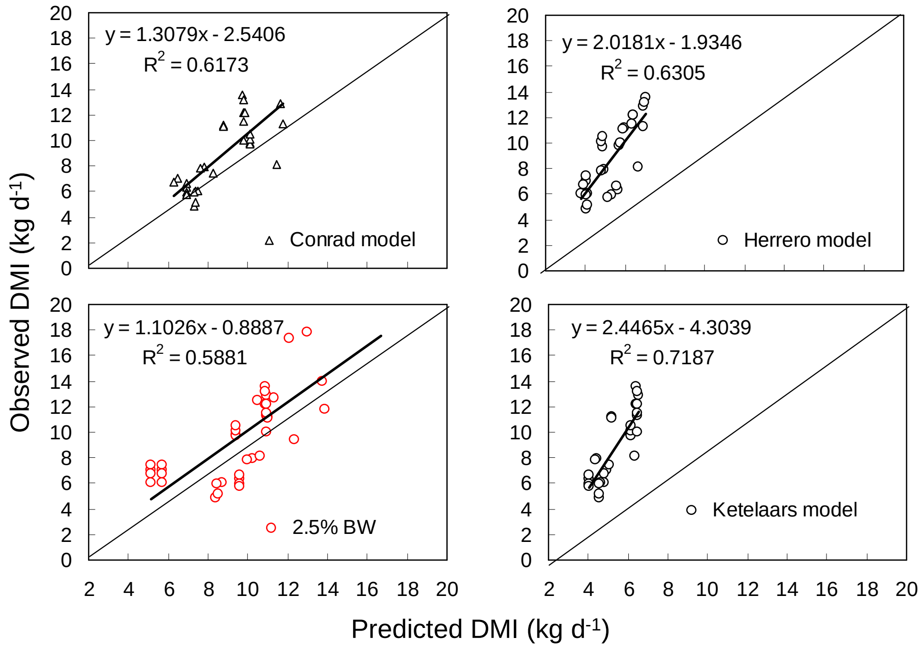


Figure A11: Observed DMI Holstein-Friesian × Zebu lactating cows plotted against predicted DMI using the Ruminant model of Herrero (1997), the Conrad model (Conrad, 1961;1966) , the model of Ketelaar and Tolkamp (1991) and the fraction of BW model.

Table A7: Results of the testing of the models of intake prediction.

| Data set | Ruminant model | Ketelaars model | Conrad model | Fraction of BW |
|---|---|---|---|---|
| Azawak steers | y = x + 1.90 | y = 0.85x + 1.98 | y = 0.92x + 1.56 | y = 0.89x + 1.54 |
| $r^2$ | 0.62 | 0.48 | 0.67 | 0.65 |
| MSPE | 4.39 | 2.94 | 2.05 | 1.69 |
| Holstein-Ayshire steers | y = 1.01x + 0.60 | y = 2.13x – 3.21 | y = 0.98x – 1.49 | y = 1.37x – 1.49 |
| $r^2$ | 0.54 | 0.67 | 0.67 | 0.67 |
| MSPE | 0.65 | 0.43 | 2.71 | 0.20 |
| Dairy cows (together) | y = 2.02x – 1.94 | y = 2.45x – 4.30 | y = 1.31x – 2.54 | y = 1.10x – 0.89 |
| $r^2$ | 0.63 | 0.72 | 0.62 | 0.59 |
| MSPE | 11.4 | 11.2 | 2.1 | 5.8 |

MSPE: mean square prediction error, $r^2$: coefficient of determination

## 2.6 Animal production under limiting conditions

When the available feed supply equals nutrient requirements, the potential production is achieved provided that there are no other limiting and reducing factors. Water requirements and reducing factors (diseases, pollutants) are not (yet) included in LIVSIM. When the nutrients provided by feed intake cannot meet the nutrient requirements for potential production, the calculated intake is used to meet the requirements of different processes according to certain rules. This is illustrated for animals in different physiological and reproductive status as case 1 for growing males and females, case 2 for pregnant females, case 3 lactating females and case 4 for pregnant and lactating females (Figs A12, A13, A14 and A15). First, it is determined whether ME or MP are limiting potential production, then the physiological and reproductive status of the animal are checked. When potential production cannot be achieved, the next check is whether the nutritive requirements for maintenance can be met. This decides which routine is executed by the model: either little growth or weight loss. Through several iterations growth and production are calculated to match the feed intake. Mortality is simulated both as a probabilistic process qualified by the age of an animal and deterministically defined by nutritional status. There is a threshold to weight loss beyond which the animal dies, for non-lactating animals this is the minimum bodyweight for a certain age calculated from the growth curve, and for lactating animals, the allowance for bodyweight loss is set to 0.8 kg weight loss per day (Herrero, 1997).

## 2.7 Calculation of excreta production

LIVSIM simulates faecal dry matter production, faecal N and urinary N. Faecal dry matter (FaecalDM) is calculated as:

$$FaecalDM = DMI \times (1 - DMD) \qquad \text{Eq. 7}$$

where DMD is dry matter digestibility, input to the model. Faecal N and urinary-N are calculated by using the metabolisable protein (MP) system of AFRC (1993).

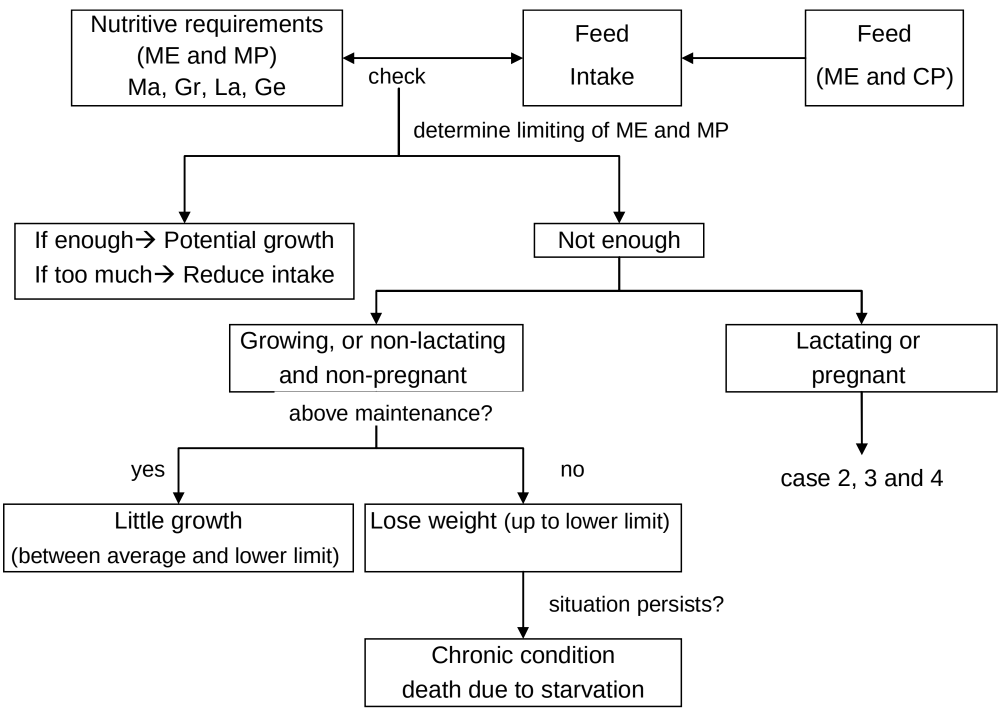


Figure A12: Growth and production routine for growing animals. CP: crude protein, ME: metabolisable energy, MP: metabolisable protein, Ma: maintenance requirements, Gr: growth requirements, La: lactation requirements, and Ge: gestation requirements.

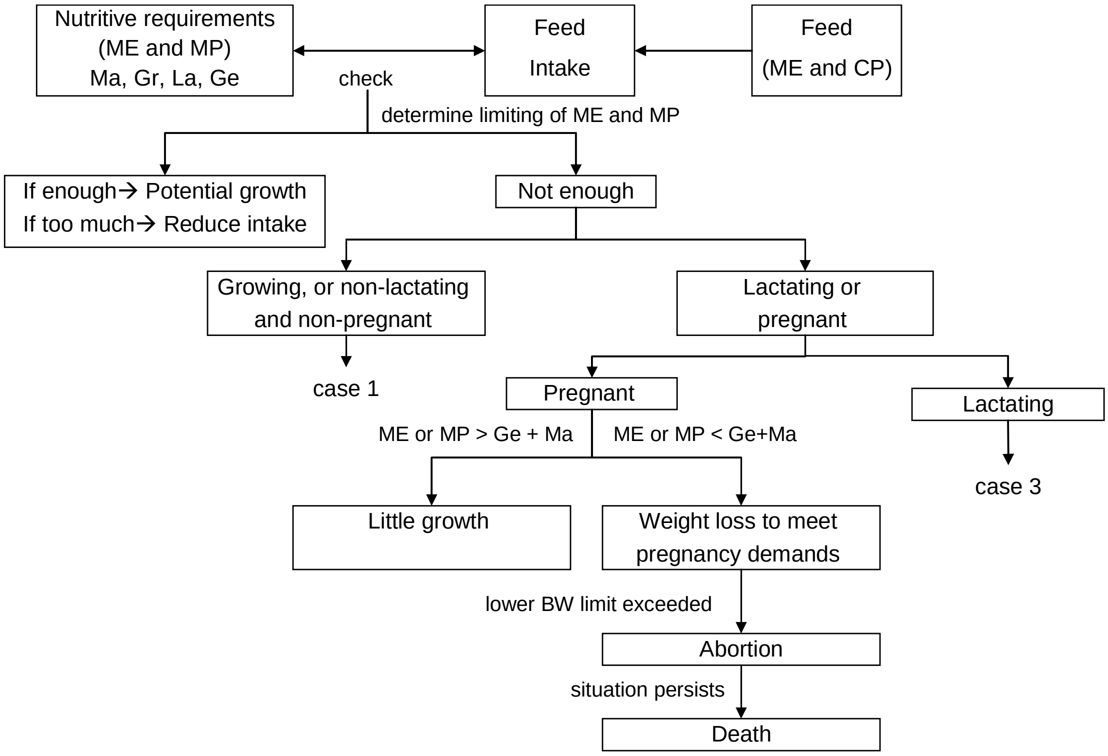


Figure A13: Growth and production routine for pregnant cows. CP: crude protein, ME: metabolisable energy, MP: metabolisable protein, Ma: maintenance requirements, Gr: growth requirements, La: lactation requirements, and Ge: gestation requirements.

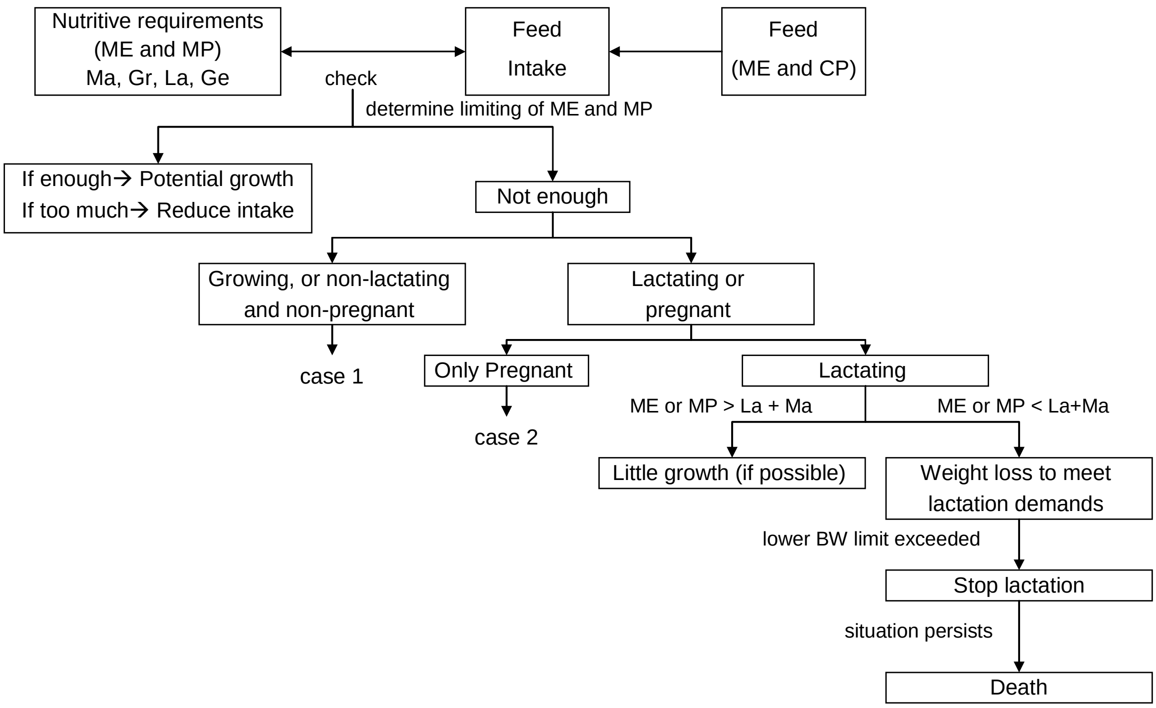


Figure A14: Growth and production routine for lactating animals. CP: crude protein, ME: metabolisable energy, MP: metabolisable protein, Ma: maintenance requirements, Gr: growth requirements, La: lactation requirements and Ge: gestation requirements.

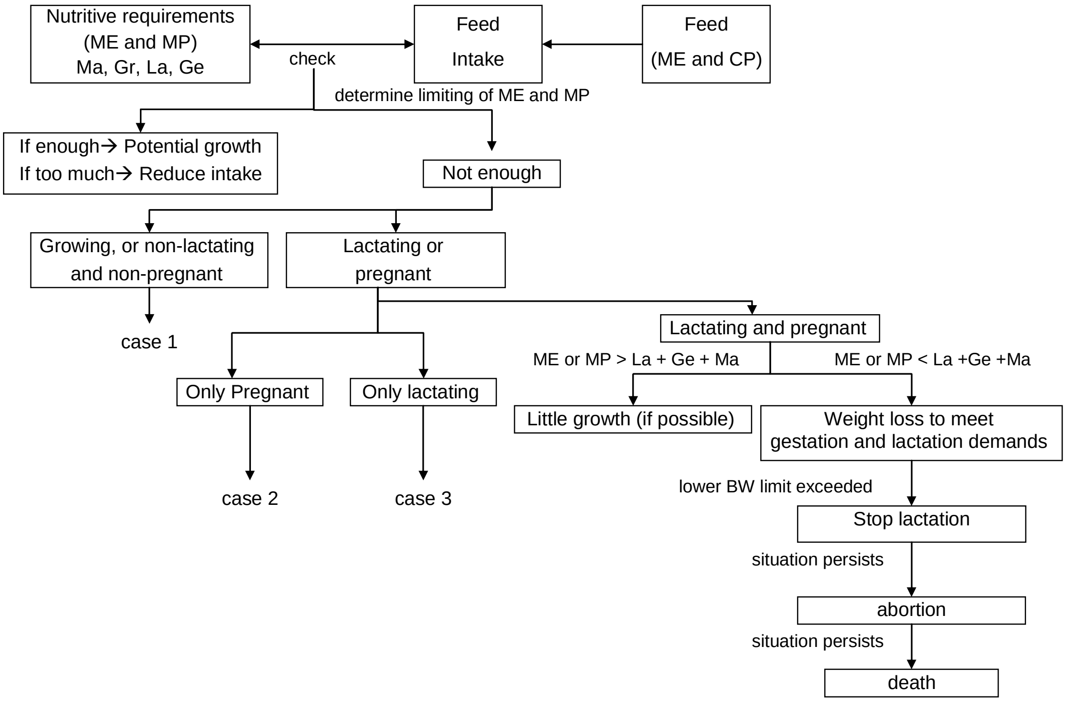


Figure A15: Growth and production routine for lactating and pregnant animals. CP: crude protein, ME: metabolisable energy, MP: metabolisable protein, Ma: maintenance requirements, Gr: growth requirements, La: lactation requirements, and Ge: gestation requirements.

Partitioning between organic N and ammonium is also important for recycling but it is not currently simulated. Detailed models may be used to generate response curves (e.g. N intake *vs* faecal-N and urinary-N) that can be incorporated into LIVSIM. An approach that will be tested for this purpose is that used in the model of Kebreab et al. (2004).

## 3. Implementation of a feeding routine

We used a simple approach in LIVSIM to deal with the complexity of selection and allocation of feeds in smallholder farming systems. In the following sections we present the concepts and main assumptions for the grazing and stall feeding routines.

### 3.1 The grazing routine

*3.1.1 General approach*

A number of models have been developed to simulate grazing in heterogeneous pastures. Breed characteristics increase the variability of observations in feeding behaviour and make it more difficult to develop a generic grazing model. The pasture-animal interface involves complex interactions between amount and quality of available herbage, animal's require-ments, their capabilities to select feedstuffs and the influence of management (Dove, 1996).

All these interactions occur at different hierarchical levels (Herrero et al., 1998). The framework of the grazing routine is presented in Fig. A16. The grazing behaviour was divided into two main components: diet selection and feed intake (Baker et al., 1992).

*3.1.2 Herbage intake*

Feed intake is described as:

$$DMI_{a,z,g} = DMPI_g \times RI_z \qquad \text{Eq. 8.}$$

where $DMI_{a,z,g}$ is dry matter intake expressed in kg DM $d^{-1}$, $DMPI_g$ is the potential dry matter intake expressed in kg $d^{-1}$, and $RI_z$ the relative intake (dimensionless). The suffix *a* refers to the animals, *g* to the grasses species and *z* to the grazing units. The potential intake (DMPI) is calculated with the model of Conrad (1964; 1966) (Eq. 9).

$$DMPI_{a,g} = 0{,}0107 \times \frac{BW_a}{(1 - DMD_g)} \qquad \text{Eq. 9}$$

where BW is bodyweight (kg), and DMD= is dry matter digestible (g (kg DM)$^{-1}$).

Potential intake does not take into account constraints imposed by herbage availability. It is adjusted by using the concept of relative intake (Herrero et al., 1998) (Fig. A17). The equation developed by Johnson and Parson (1985) was adapted (Eq. 10). The original equation describes relative intake as a function of leaf area index (LAI). We adapted the equation using dry matter herbage mass, similarly to the approach used by Richardson et al. (1991).

$$RI_{z,g} = \frac{(Ba_{z,g} / K)^q}{1 + (Ba_{z,g} / K)^q} \qquad \text{Eq. 10}$$

Where *q* and *K* are dimensionless coefficients. *K* describes the capability of an animal to graze. This empirical relationship does not take into account the influence of animal body size to regulate intake (Illius, 1989). The coefficient *K* was scaled to animal body weight using an allometric relationship derived from Illius and Gordon (1989), as proposed by Herrero et al. (1998; 2000). Coefficients *b* and *q* were calculated by fitting the curve to data reported by Herrero et al. (1998).

$$K = b \times BW^{0.36} \qquad \text{Eq. 11}$$

where *b* is dimension less coefficient. The chosen approach takes into account both herbage biomass and the animal's capability to harvest grasses (Fig. A17).

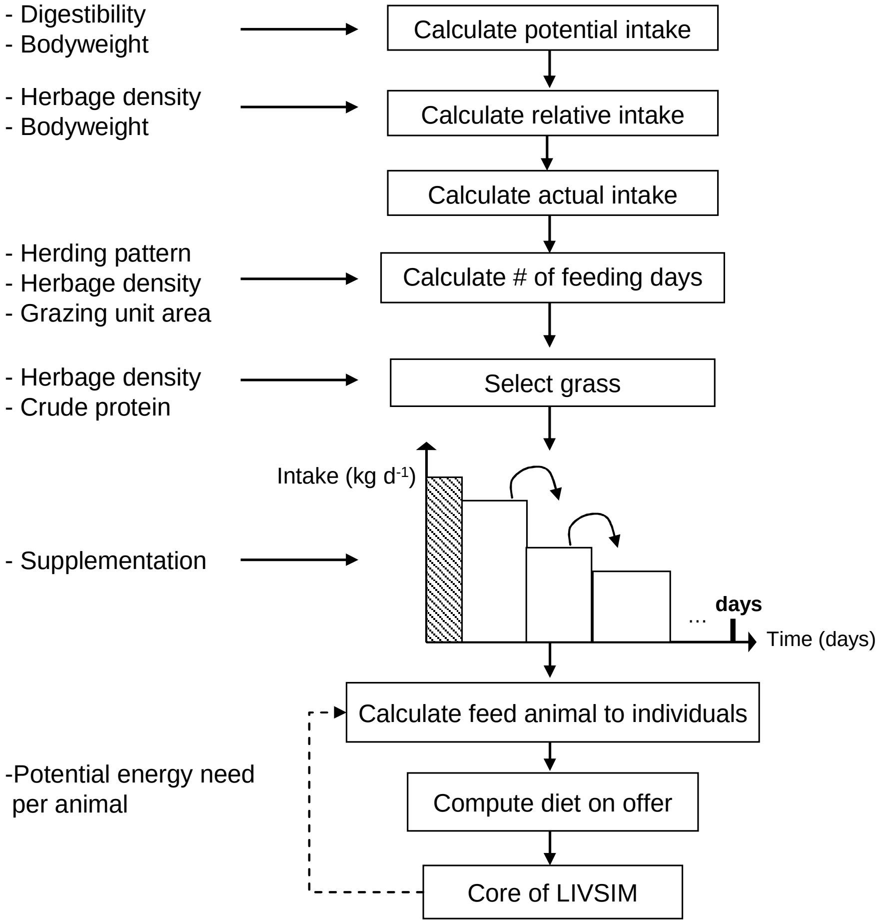


Figure A16: Flow chart of the feeding routine as implemented in LIVSIM. Intake is a function of grass quality (dry matter digestibility, DMD), bodyweight (BW) and herbage density. The number of feeding days is the number of days that the available forage can support the animal at the rate of intake previously calculated. Grass is selected on the basis of its crude protein (CP) content. The allocation of feed is based on the animals' energy requirements.

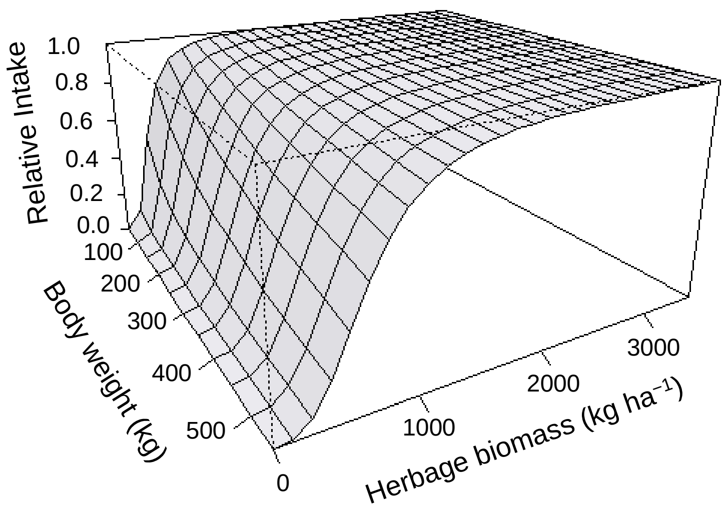


Figure A17: Relationship between bodyweight, herbage biomass and relative intake (RI) (adapted from Herrero et al., 2000).

*3.1.3 Herbage selection*

There is general agreement that ruminants consume a diet with a higher quality than the average quality of the pasture (e.g. Elliott and Fokkema, 1961). The nutrient content in the diet selected is mainly influenced by the seasonal variation in the quality of the vegetation and selection between different species and/or part of the plants (Schlecht et al., 1999). The influence of the spatial-distribution on the diet selection was treated at different levels based on the concept developed by Senft et al. (1987) in their hierarchical foraging model. Animal management was integrated into this concept by taking into account herding strategies. The main advantage of this approach is its simplicity and its compatibility with the temporal scale of management (Senft, 1989). We considered different levels of interaction between animals and feed resources (Fig. A18). At the species or plant part level, selection is accounted for by using a preference index based on crude protein content and abundance of plant and/or plant parts. A species is preferred if its proportion in the grass on offer is larger than the proportional biomass within the grazed area (Senft, 1989). Relative crude protein content (RCP) was chosen as criterion of grass quality. Several authors have showed the positive correlation crude protein (CP) and diet composition (Breman and De Wit, 1983; Baker et al., 1992; Cilliers and Van der Merwe, 1993).

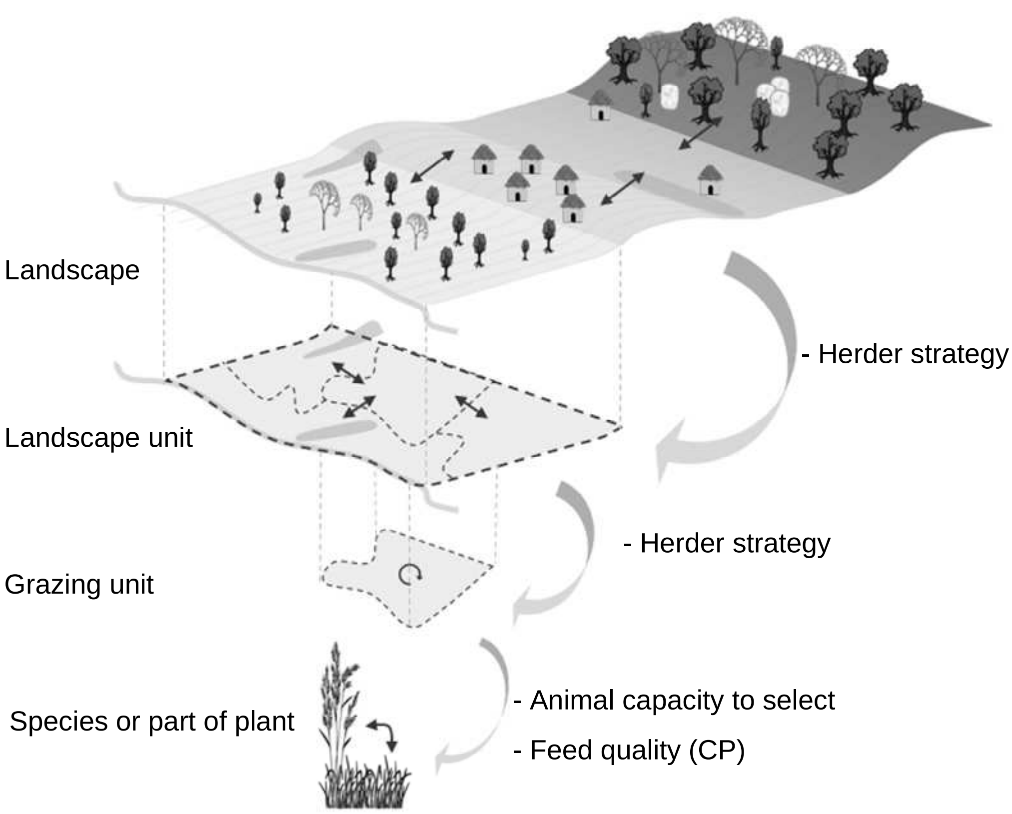


Figure A18: Animal/plant interactions considered in the grazing routine for grass selection. See Section 3.1.3 for further explanation.

The equations developed by Senft (1989) were used for ranking feeds according to cattle preference:

$$RCP_{z,g} = \frac{CP_g \times Ba_{z,g}}{\sum_{g=1}^{n}(CP_g \times Ba_{z,g})} \qquad \text{Eq. 12}$$

where *RCP* is relative crude protein preference index (dimensionless), *CP* is the crude protein content of each dominant grass (g) expressed in g kg DM$^{-1}$, and *Ba* is herbage density expressed in kg DM ha$^{-1}$. In this approach we assume that herders choose the land unit for grazing. This is captured as the time spent at each grazing unit expressed in days per month and is input to the model. Based on forage quality, animal body weight and herbage constraint, the quantity of forage that an animal can consume per day is calculated. From the available forage, the numbers of feeding days were calculated as:

$$FD_g = \frac{Bm_g \times DMuse}{\sum_{a=1}^{n} DMI_g} \qquad \text{Eq. 13}$$

where *FD* is feeding days (days), *DMuse* is harvestable forage (g) in a grassland, set to 50% for rainy season and 30% for the dry season (Breman and De Wit, 1983; De Ridder and Breman, 1993) and *Bm* is total grass biomass (kg). Feeding days of each dominant grass were summed following the ordering of the preference ranking. The iteration stops when the sum reaches the time spent by the animals within a grazing unit. Time spent in a grazing unit is described by the herding pattern.

### *3.1.4 Feed allocation between animals of a herd*

All previous calculations are aggregated to calculate the intake of the entire herd. Allocation coefficients were calculated for each individual animal. Allocations were based on energy requirements for each individual animal. Energy and protein requirements are calculated using the energy and protein system of AFRC (1993). The following equations were used to allocate feeds in a herd:

$$Diet_{a,g} = Allocation\_factor_a \times Diet_g \qquad \text{Eq. 14}$$

$$Allocation\_factor_a = \frac{Energy\_pot_a}{\sum_{a=1}^{n} Energy\_pot} \qquad \text{Eq. 15}$$

where $Diet_{a,g}$ is the amount of feed on-offer for an individual animal, $Diet_g$ is a matrix that contains the amounts of grass species available, expressed in kg DM, the *Allocation_factor* is a coefficient (MJ $MJ^{-1}$) to allocate the feed to the animals of a herd, and *Energy_pot* is the energy requirement to achieve potential production, expressed in MJ. It is assumed that competition between animals due to social hierarchy is negligible, which means that individuals graze to meet their nutritive requirements.

## 3.2 Stall feeding routine

Calculations of feed on-offer during stalling follow the same setup as presented in the grazing routine. Here it was assumed that there are no constraints imposed by the herbage mass availability. Selection takes place on the basis of crude protein.

## 4. Model input and parameters

The initial composition of the herd is an input to the model. To start the simulation, a list of animal and feed characteristics needs to be provided (Table A8). Parameters for cross bred Friesian × Zebu were presented with the description of LIVSIM, in the next sections we present parameters for the Mashona and Africander breeds.

Table A8: List of animal and feed characteristics that are inputs/outputs to LIVSIM.

| | Variable | Units |
|---|---|---|
| 1 | Sex | – |
| 2 | Age | y |
| 3 | Initial bodyweight | kg |
| 4 | Reproductive status | |

Table A9: Feed quality parameters (from AFRC, 1993). Nitrogen degradation parameters: a = proportion of water soluble N in the total N in a feed; b = proportion of potentially degradable N other than water soluble N in the total N of the feed; c = fractional rumen degradation rate per hour of the b fraction of the feed N with time (AFRC, 1993).

| | Variable | Units |
|---|---|---|
| 1 | Dry matter content | g $kg^{-1}$ |
| 2 | Metabolisable Energy (ME) | MJ kg $DM^{-1}$ |
| 3 | Fermentable Energy (FE)[1] | MJ kg $DM^{-1}$ |
| 4 | Crude protein (CP) | g kg $DM^{-1}$ |
| 5 | Acid Detergent Insoluble N (ADIN) | g kg $DM^{-1}$ |
| 6 | (a) | fraction |
| 7 | (b) | fraction |
| 8 | (c) | fraction |
| 9 | Dry matter digestibility (DMD) | g kg $DM^{-1}$ |

[1] Only needed for silages

## 4.1 Mashona breed

### *4.1.1 Growth curve*

The growth curve for Mashona cattle was estimated using data available from literature for and on-farm measurements (Fig. A19).

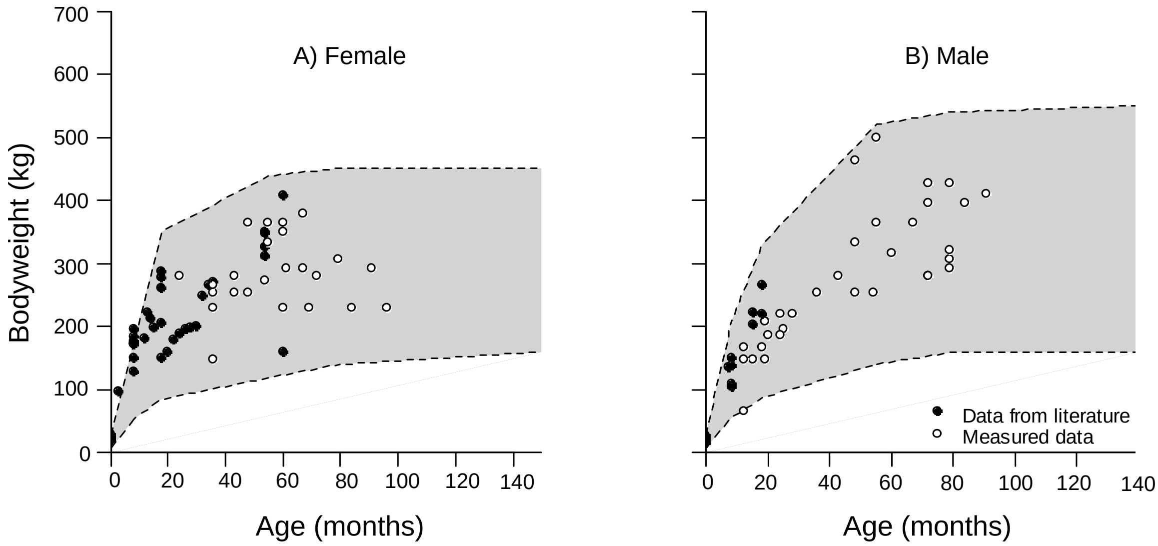


Figure A19: Potential growth curve for female (A) and male (B) Mashona cattle. Sources: Tawonezvi et al., (1988); Tawonezvi, (1989); Tiffin, (1989); Moyo, (1990); Payne, (1990); Holness, (1992); Khombe et al., (1994); Matizha et al., (1995); Hatendi, (1996); Pedersen and Madsen, (1998); Mhlanga et al., (1999).

### *4.1.2 Reproduction*

The parameters for reproduction were derived from literature (Table A10).

Table A10: Parameters for defining the feasible set of bodyweight-age combinations for conception of Mashona.

| Parameter | Value | Source |
|---|---|---|
| Minimum age first calving in the best condition (months) | 15 | Tiffin (1989) |
| Average age at first calving in poorest condition (months) | 27.7 | Holness (1992) |
| Maximum age first calving in the poorest condition (months) | 36 | Holness (1992) |
| Average annual calving rate within this age interval (year$^{-1}$) | 0.74 | Moyo (1990) |
| Age less than $t_2$ for which the calving rate is known (year$^{-1}$) | 15 | Tiffin (1989) |
| Average calving rate at age $t_1$ (year$^{-1}$) | 0.57 | Tiffin (1989) |
| Calving interval (days) | 447.8 (11.4)[1] | Moyo (1990) |
| Gestation length (days) | 285.9 (13.2) | Holness (1992) |
| Average birth weight (female) (kg) | 21 | Payne (1990) |
| Average birth weight (male) (kg) | 23 | Payne (1990) |
| Mature body weight (female) (kg) | 350 | Roy (1980) |
| Mature body weight (male) (kg) | 380 | Roy (1980) |
| Milk fat (g kg$^{-1}$) | 33 | Mhlanga et al. (1999) |
| Milk protein (g kg$^{-1}$) | 32 | Mhlanga et al. (1999) |

[1] Standard deviation

*4.1.3 Milk production*

The milk production curve was calculated according to Konandreas and Anderson (1982) using data from the literature.

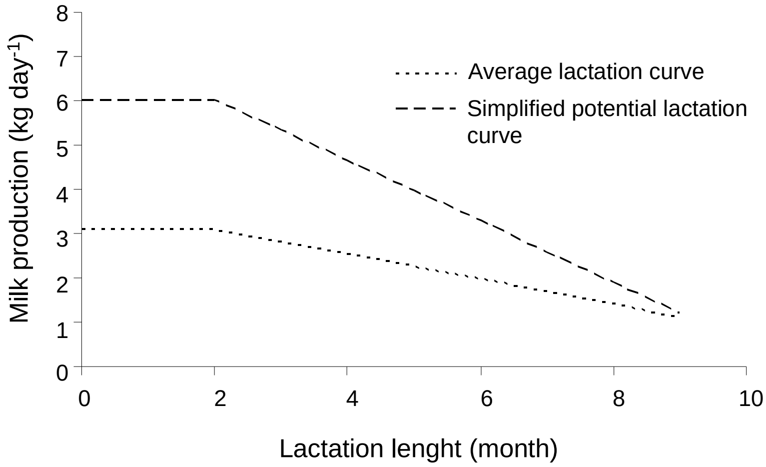


Figure A20: Simplified lactation curve for Mashona. After Konandreas and Anderson (1982). Sources: Potential milk production curve Holness, (1992), and average curve Holness (1992); Hatendi, (1996); Pedersen and Madsen (1998); Masama et al. (2003).

## 4.2 Africander breed

*4.2.1 Maximum and minimum growth curves*

The data used for estimating growth curves was collected over a 40 years period at Matopos Research Station (Beffa, 2005). The dataset contains about 180,000 measurements. Bodyweight of 4443 animals of their respective dams (n=1330) were monitored during the 30 months after calving. From these data, potential growth curve and minimum bodyweight-age combination were estimated.

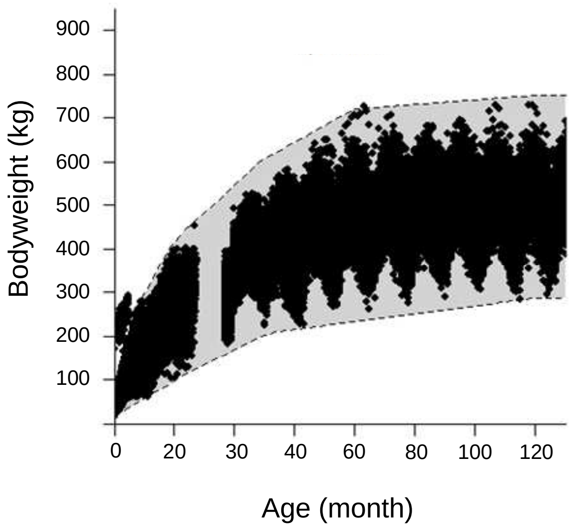


Figure A21: Potential growth curve for Africander female cattle. Source: Database from Matopos research station (Beffa, 2005).

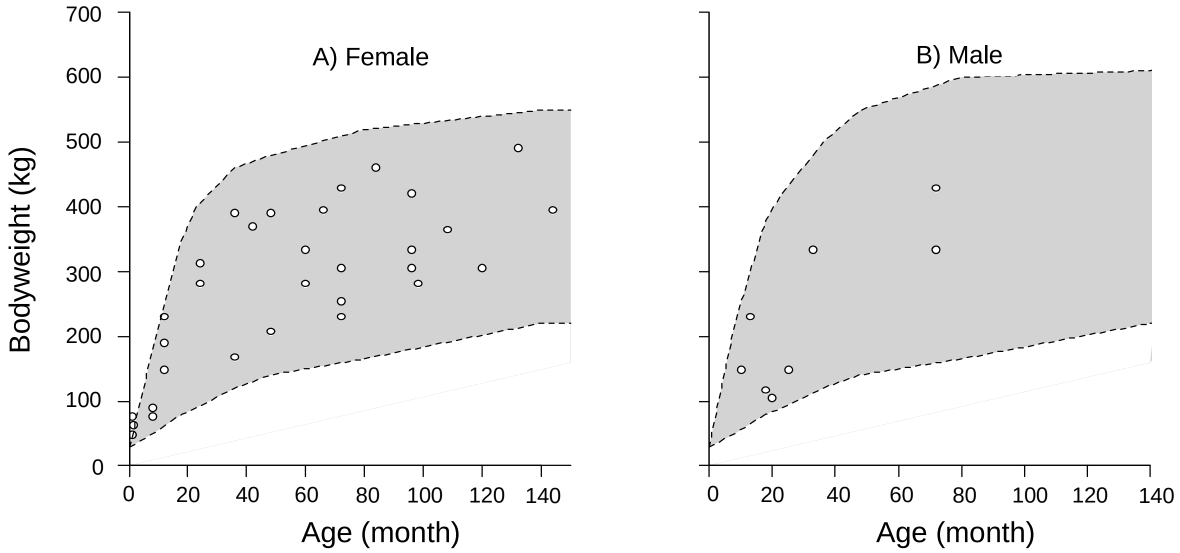


Figure A22: Potential growth curve for Africander crossbred cattle based on observed bodyweight measurements.

As few pure Africander were found in Murewa, the minimum and the maximum growth curve for Africander crossbred were also defined based on observed bodyweight in smallholder farms in the communal area of Murewa in Zimbabwe (Dury, 2007).

*4.2.2 Reproduction*

The annual calving rate (%) was calculated and plotted against age of the cow. Annual calving rates (%) were used to calculate the same theoretical relationship as proposed by Konandreas and Anderson (1982).

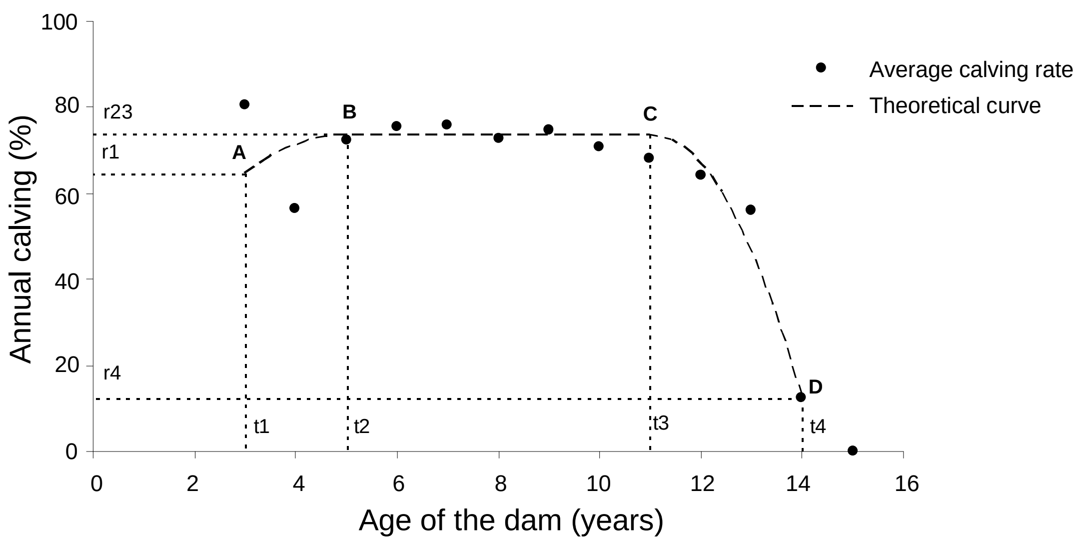


Figure A23: Reproduction parameters for Africander cattle Source: Database from Marondera research station (Beffa, 2005).

Data from the literature was used for defining the feasible set of bodyweight-age combination for conception. The simplified average and potential milk production curve was also estimated with data from the literature.

Table A11: Parameter for defining the feasible set of bodyweight-age combinations for conception for Africander cows. See Fig. A 23 and Konandreas and Anderson (1982) for further explanation of the derivation of reproduction parameters.

| Parameter | Value | Source |
|---|---|---|
| Minimum age first calving in the best condition (months) | 24 | Meaker et al. (1982) |
| Average age first calving in poorest condition (months) | 36 | Mukasa-Mugerwa, (1989) |
| Maximum age first calving in the poorest condition (months) | 36 | Holness (1982) |
| Age interval when cows achieve maximum fertility (month) | 30−132 | Beffa (2005) |
| Average annual calving rate for cow within this age interval | 0.73 | Beffa (2005) |
| Age < than $t_2$ for which the calving rate is known (month) | 36 | Beffa (2005) |
| Average calving rate at age $t_1$ | 0.65 | Beffa (2005) |
| Age > $t_3$ for which the calving rate is known ($t_4$) (month) | 144 | Beffa (2005) |
| Average calving rate at age $t_4$ ($y^{-1}$) | 0.1 | Beffa (2005) |
| Calving interval (days) | 540 (13)[1] | Moyo (1990) |
| Gestation length (days) | 298 (13.2) | Holness (1982) |
| Average birth weight female (kg) | 30.4 | Beffa (2005) |
| Average birth weight male (kg) | 35.5 | Beffa (2005) |
| Mature body weight females (kg) | 490 kg | Roy (1980) |
| Mature body weight male (kg) | 570 kg | Roy (1980) |

[1] Standard deviation

*4.2.3 Milk production*

Milk production curve for Africander cattle was defined with data from the literature.

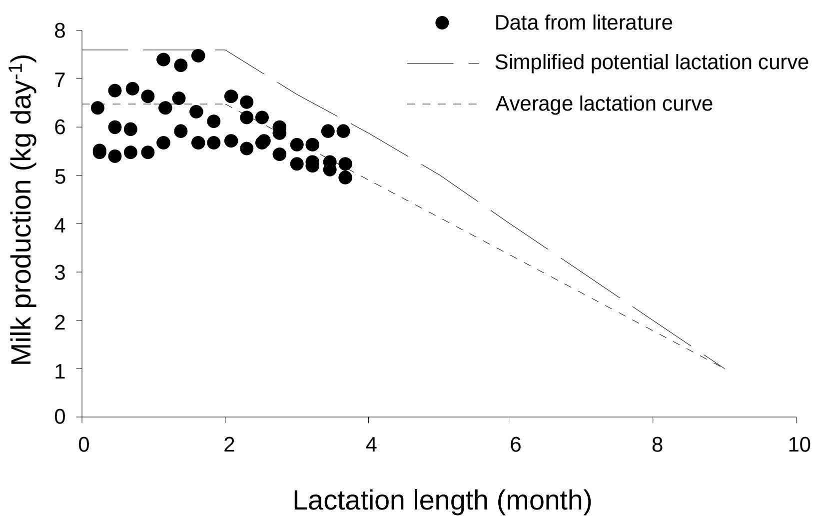


Figure A24: Potential and average milk production for Africander cattle. Source: Richardson (1968).

## 5. Running the model

For the simulations we use a monthly time step because it suffices the purposes of our studies and allow easy coupling with the farm scale model FARMSIM. Because the model simulates discrete event by using stochastic variables, replicated runs are needed to estimate the output variables. We performed experiments to evaluate the minimum number of replicates that capture the effect of the treatments. The experiments were performed using the common feeding practice of the dairy smallholders (Napier grass and two kg of concentrates offered only to lactating animals) and using the parametersation for the Holstein-Friesian × Zebu breed. Model outputs were analysed with the Kruskal Wallis non-parametric test. Differences between run-lengths were not-significant (Table A12).

Table A12: Experiments with run lengths and lifetime productivity indicators. Basal diet consisting of Napier grass supplemented with 2 kg of concentrates during lactation. Lifetime is considered to be 12 years for crossbred dairy cattle in smallholder systems of the highlands of Central Kenya.

| Run length | 100 | 500 | 1000 | 5000 | 10000 | KW |
|---|---|---|---|---|---|---|
| Output variables | | | | | | test |
| Calves (# per lifetime$^{-1}$) | | | | | | |
| Mean ± s.e | 5.8 ± 0.10 | 5.7 ± 0.05 | 5.7 ± 0.03 | 5.7 ± 0.01 | 5.7 ± 0.01 | |
| Median | 6 | 6 | 6 | 6 | 6 | 1.7$^{ns}$ |
| Range | 4-8 | 3-8 | 2-8 | 1-9 | 1-9 | |
| Cumulative milk (kg lifetime$^{-1}$) | | | | | | |
| Mean ± s.e | 9,759 ± 125 | 9,642 ± 63 | 9,612 ± 45 | 9,666 ± 20 | 9,675 ± 14 | |
| Median | 9,950 | 9,793 | 9,815 | 9,818 | 9,852 | 2.4$^{ns}$ |
| Range | 6,051-11,854 | 4,267-12,392 | 3,734-12,395 | 1,817-12,306 | 1,870 -12,542 | |
| Days in milk (days lifetime$^{-1}$) | | | | | | |
| Mean ± s.e | 1,666 ± 28 | 1,654 ± 13 | 1,645 ± 9 | 1,653 ± 4 | 1,655 ± 3 | |
| Median | 1,703 | 1,703 | 1,673 | 1,703 | 1,703 | 1.6$^{ns}$ |
| Range | 943-2,312 | 639-2,403 | 578-2,373 | 304-2,525 | 304-2,616 | |
| Days open (days lifetime$^{-1}$) | | | | | | |
| Mean ± s.e | 1,579 ± 29 | 1,627 ± 13 | 1,607 ± 10 | 1,611 ± 4 | 1,604± 3 | |
| Median | 1,612 | 1,612 | 1,582 | 1,582 | 1,582 | 1.3$^{ns}$ |
| Range | 913-2,281 | 700-2,585 | 821-2,646 | 578-2,798 | 365-2,920 | |

## 6. Model evaluations

Model fine tuning or fitting is the estimation of values of parameters or unmeasured variables using available information from the real system (Tedeschi, 2006). We used a number of independent datasets to calibrate the different modules of LIVSIM. The goals were to measure model adequacy based on pre-established criteria of model performance acceptance such as functionality, accuracy, and precision for its intended purpose.

### 6.1 Test using data from Zebu steers

Data on feed intake and feed quality, and evolution of bodyweight and age of 86 steers that were grazed on-station in Sadoré, Niger was obtained from Ayantunde (1998); Ayantunde et al., (2001). Feed intake was estimated from individual data on faecal output, and therefore the intake function of the model was not used. In this preliminary test, we evaluated the growth routine of LIVSIM. We selected a number of individual for isolated test for which age and initial bodyweight are known. The simulations of bodyweight are presented in Figs. 25A, B and C. Then we calculated the statistics of the herd (n=86), and used this as initial bodyweight for the simulations. Results are presented in Fig. 23D. The model simulations show good agreement with the observed data for individual animals and for all the animals together.

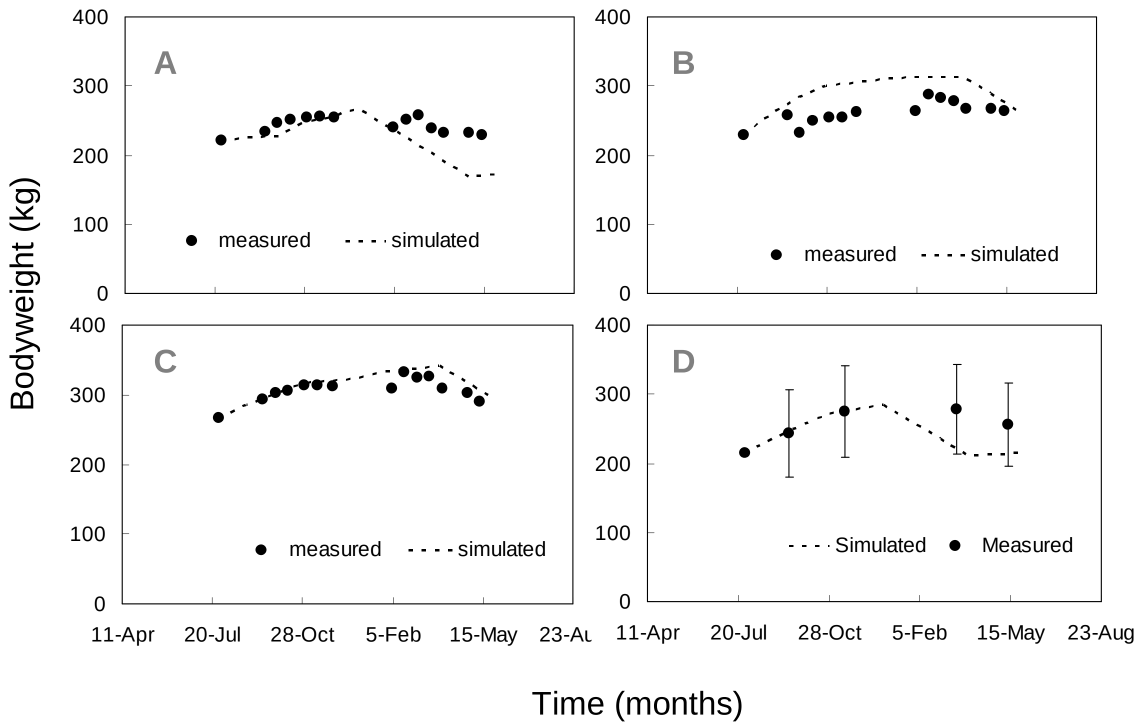


Figure A25: Model testing using a dataset for steers grazing in a pasture in Niger. Figs A, B and C show predictions for individual animals and figure D for all animals together (n=86). Data sources: Ayantunde (1998) and Ayantunde et al. (2001).

### 6.2 Test using data from lactating Holstein-Friesian × Boran cows

Data on age, evolution of bodyweight, feed intake and feed quality from 24 cross bred Friesian Holstein × Boran cows was obtained from Jenet et al. (2004). These cows are fed different diets based equivalent to 1, 1.2 and 1.4 times the energy requirements as suggested by MAFF (1987). Diet consisted of Bermuda grass (*Cynodon dactylon* L.) hay (65% of the diet), supplemented with wheat bran (35% of the diet). The quality of the diet is presented in Table A13. Cows were 3.7 ± 0.2 and 4.9 ± 0.3 years and at the beginning of the first and second lactation and the bodyweight 360−420 kg according to the feeding level and 350−410 kg at the start of the first and second lactations.

Table A13: Quality parameters of the feedstuffs used in the test with dairy cows in the model simulations DM=dry matter; DMD=dry matter digestibility; ME=metabolisable energy; CP =crude protein; a = proportion of water soluble N in the total N in a feed; b = proportion of potentially degradable N other than water soluble N in the total N of the feed; c = fractional rumen degradation rate per hour of the b fraction of the feed N with time (AFRC, 1993).

| Feeds | DM (g kg$^{-1}$) | DMD (g kg$^{-1}$) | ME MJ (kg DM)$^{-1}$ | CP g (kg DM)$^{-1}$ | a | b | c |
|---|---|---|---|---|---|---|---|
| Bermuda grass | 905 | 590 | 9.6 | 45 | 0.22 | 0.60 | 0.08 |
| Wheat bran | 890 | 700 | 11.0 | 160 | 0.30 | 0.57 | 0.11 |

Source: Jenet et al. (2004b).

We selected the low (maintenance) and high (1.4 × maintenance) feeding rates for the test. Intake of the cows for the low level (maintenance) was in average 3.2 ± 0.1 kg of hay per day and 1.8 ± 0.1 kg wheat bran per day for the whole lactation period. For the high feeding rate (1.4 × maintenance), intake was 5.1 ± 0.3 of hay and 2.8 ± 0.2 kg wheat bran per day. The results of the tests of bodyweight evolution are presented for high (Fig. A26A and C) and low (Fig. A26B and D) feeding rates and for the first (Fig. A26A and B) and second lactations in (Fig. A26C and D).

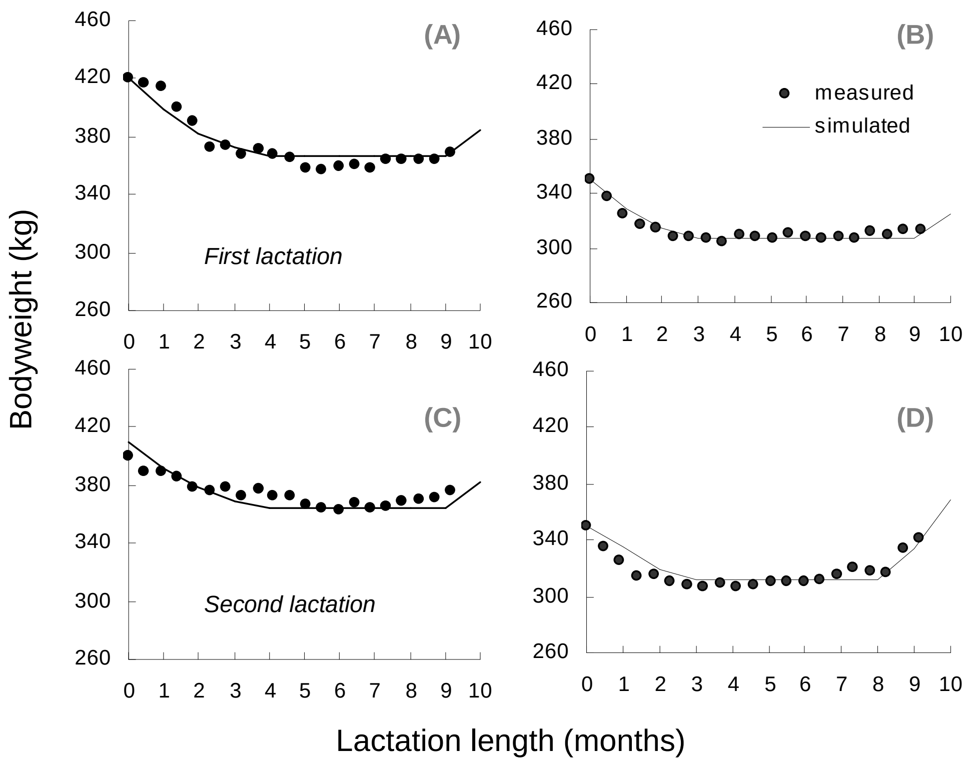


Figure A26. Development of simulated and measured bodyweight for lactation Friesian × zebu cows under two feeding levels: high (1.4 × maintenance) (A and C), and low (maintenance) (B and D), for first lactation (A and B) and second lactation (C and D).

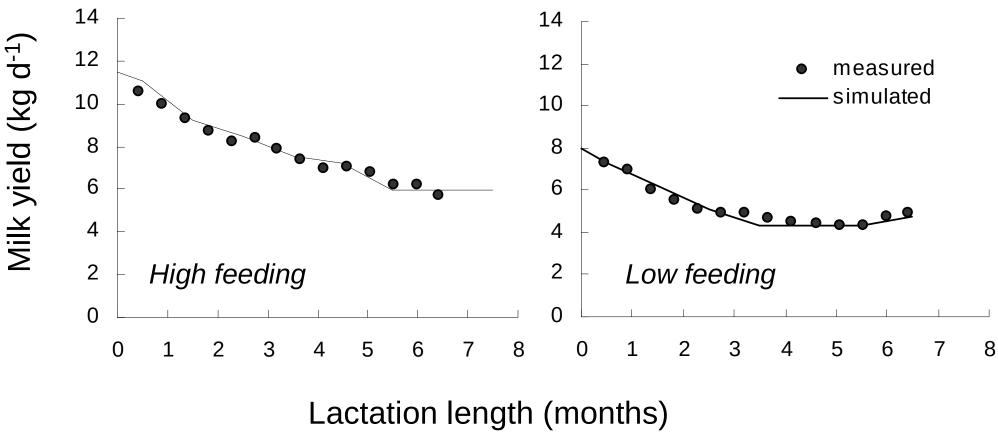


Figure A27. Development of simulated and measured milk production for Friesian × zebu cows under two feeding levels: high (1.4 × maintenance) and low (1 × maintenance).

There were differences in the weight loss at the beginning of the lactation of cows from the first parturition compared with cows of the second parturition. This had to be calibrated in the model with the bodyweight loss allowance, and it is probably breed dependent (Friggens and Newbold, 2007), and it needs to be tested for each situation in which LIVSIM is going to be applied. The best fits were obtained with a maximum bodyweight allowance of 0.7 kg per day for the first parturition and 0.6 kg per day for the second parturition. The bodyweight allowance mirrored the lactation curve. The normalised root of the square mean errors (NRMSE) were 15 and 17% for the high feeding rate and first and second lactations, and 7 and 10% for the low feeding rate and first and second lactation respectively. The differences in milk yields were larger between feeding levels than between lactations (Fig. A27). Using the curve of potential milk production from the original parameterisation (Fig. A8), gave a good fit to the experimental data of Jenet et al. (2004b). The N RMSE was 9% for the high feeding rate and 7% for the low feeding rate.

## 6.3 Tests using data from Mashona and Africander cattle

LIVSIM was evaluated with experimental data from Zimbabwe published by Elliott and Fokkema (1961a; 1961b). Intake of organic matter and protein were used as inputs to the model. The model outputs were compared to bodyweight evolution and faeces production. Details on the calculations are presented in Table A14. Simulations over two periods of seven or eight months were carried out for dry and lactating Mashona cows and dry Africander cows.

### *6.3.1 Data processing*

Elliott and Fokkema (1961a; 1961b) carried out a two year experiment on herbageconsumption by cattle in southern Zimbabwe. Based on previous experiment describing the relationship of faecal production and intake, they estimated herbage intake of Mashona and Africander under grazing condition. Three components of intake were described: organic matter ($OM_e$), digestibility of consumed organic matter ($DOMD_e$) and digestible crude protein ($DCP_e$) (Fig. A28). Inputs for feed quality were obtained from the literature (Table A15).

Table A14: Means percentage digestibility of consumed organic matter per animal breed and status. Source Elliott and Fokkema (1961a; 1961b).

| | $DCP_e$ (kg $d^{-1}$) | | | $DOMD_e$ (kg $d^{-1}$) | | |
|---|---|---|---|---|---|---|
| | Dry | Lactating | Means | Dry | Lactating | Means |
| Africander | 0.47 | 0.55 | 0.51 | 4.23 | 5.06 | 4.64 |
| Mashona | 0.34 | 0.48 | 0.41 | 3.08 | 4.29 | 3.69 |
| means | 0.40 | 0.52 | | 3.66 | 4.67 | |
| | $OM_e$ (kg $d^{-1}$) | | | $D_e$ (%) | | |
| | Dry | Lactating | Means | Dry | Lactating | Means |
| Africander | 7.79 | 9.32 | 8.56 | 53.31 | 52.58 | 52.94 |
| Mashona | 5.62 | 7.63 | 6.62 | 53.71 | 54.78 | 54.25 |
| means | 6.70 | 8.48 | | 53.51 | 53.68 | |

Table A15: Equation used for the estimation of feed quality parameters. $OM_e$ : organic matter intake, $DOMD_e$: digestible dry organic matter and $DCP_e$: digestible crude protein intake; all are expressed in kg $d^{-1}$

| Variables | Calculations | Sources | Units |
|---|---|---|---|
| Dry matter consumption (DM) | $DM = OM_e / 0.9$ | Mupangwa et al. (2002) | kg $d^{-1}$ |
| Metabolisable Energy (ME) | $ME = 0.0157 \times \frac{DOMD_e}{DM}$ | AFRC (1993) | MJ (kg DM)$^{-1}$ |
| Fermentable Energy (FE) | $FE = ME$ | | MJ (kg DM)$^{-1}$ |
| Dry matter digestibility (DMD) | $DMD = \frac{DOMD_e}{DM} \times 0.9 \times 1000$ | Mupangwa et al. (2002) | g (kg DM)$^{-1}$ |
| Crude protein (CP) | $CP = \frac{DCP_e}{DM} \times DMD$ | | g (kg DM)$^{-1}$ |
| Acid Detergent Insoluble N (ADIN) | | Estimated from AFRC (1993) | g (kg DM)$^{-1}$ |
| a | 0.25 | DYNAFEED database (ILRI) | g (kg CP)$^{-1}$ |
| b | 0.55 | | g (kg CP)$^{-1}$ |
| c | 0.125 | | g (kg CP)$^{-1}$ |

The model simulated bodyweight changes reasonably well (Fig. A29). The NRMSE was 6% for all tests (Table A16). For the breed Africander LIVSIM predicted bodyweight with a residual error smaller than 5% over a period of 7−8 months. The NRMSE of the prediction of faecal dry matter (Table A17) was slightly higher than for bodyweight but still satisfactory.

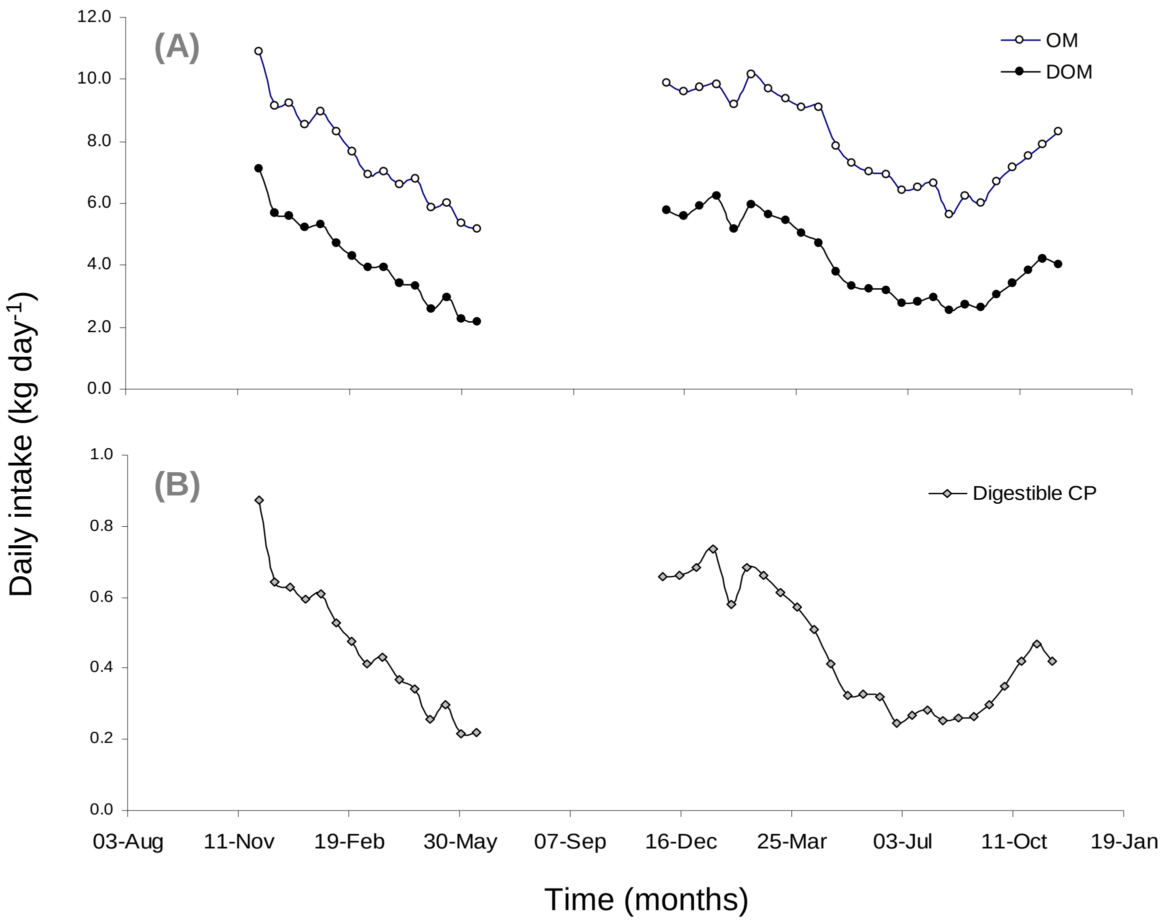


Figure A28: Seasonal change in intake of organic matter ($OM_e$) and digestible organic matter ($DOMD_e$) (A) and digestible crude protein ($DCP_e$) (B). Source: Elliott and Fokkema (1961a; 1961b). Differences between breeds and stage are presented in Table A14. We assumed constant differences over time in order to calculate specific OM, DCP and DOMD for the two breeds and two different physiological stages.

Table A16: Normalized root mean squared errors for the estimations of bodyweight (%).

| Breed | Dry | Lactating | Total |
|---|---|---|---|
| Mashona | 7 | 10 | 8 |
| Africander | 4 | 4 | 4 |
| Total | 5 | 7 | 6 |

Table A17: Normalized root mean squared errors for the estimation of faecal dry matter production (%).

| Breed | Dry | Lactating | Total |
|---|---|---|---|
| Mashona | 11 | 11 | 11 |
| Africander | 28 | 5 | 18 |
| Total | 20 | 9 | 18 |

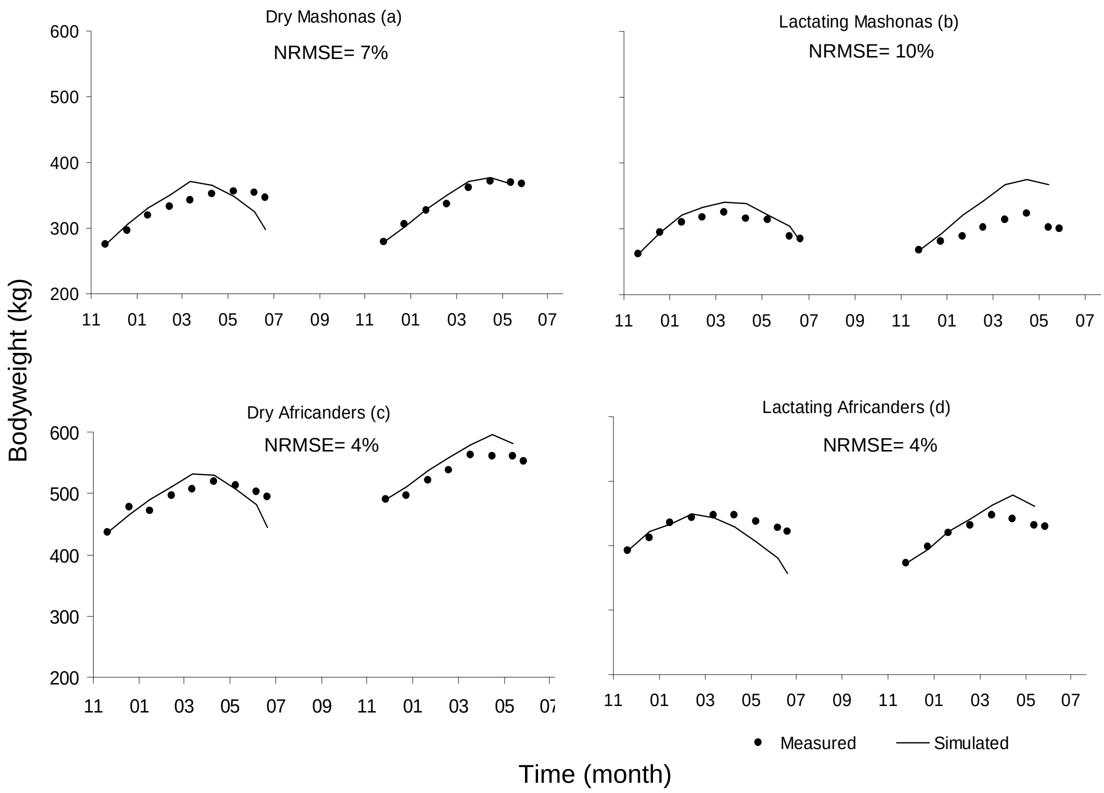


Figure A29: Bodyweight simulated with LIVSIM (full line) and bodyweight measured (dots) Sources: Elliott and Fokkema (1961a; 1961b).

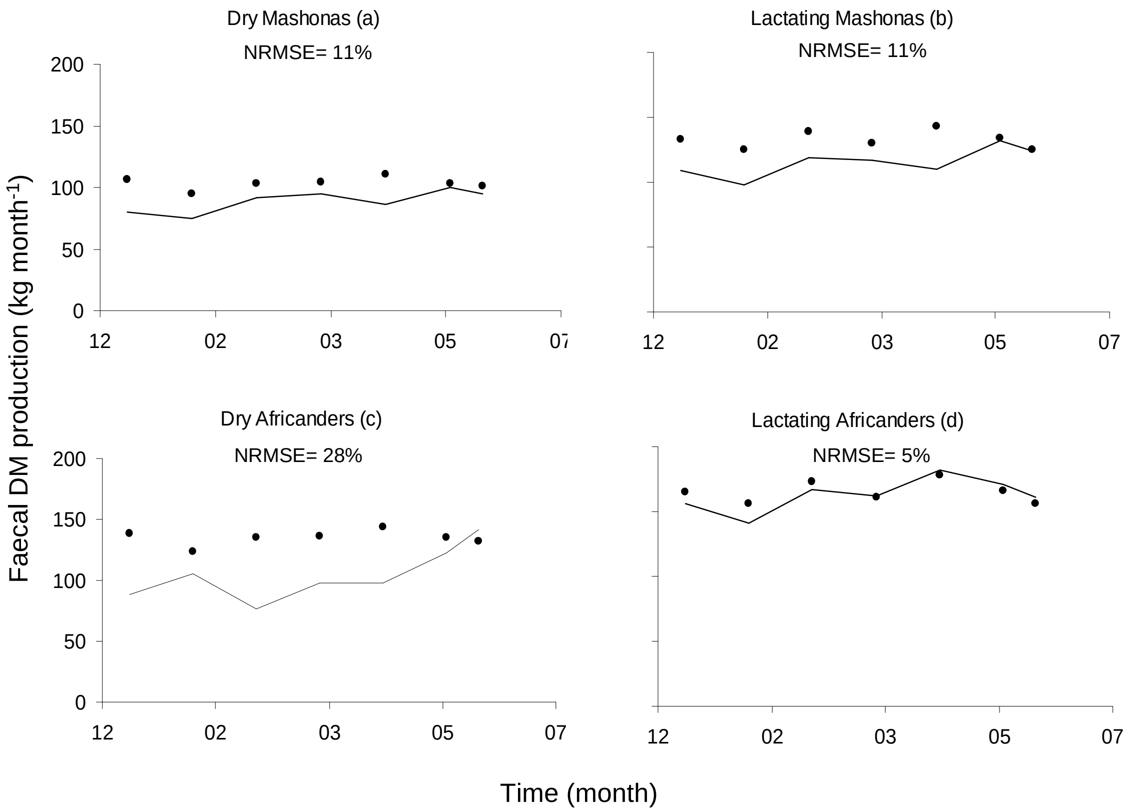


Figure A30: Faecal output simulated (full lines) with LIVSIM and measured (dots) Sources: Elliott and Fokkema (1961a; 1961b).

## 7. Recommendations for model improvement

The performance of the model is reasonable, although it appears that LIVSIM overestimates both bodyweight gain and bodyweight losses. We need to perform more evaluations on this aspect of the model. Availability of data from the breeds that are used in Sub-Saharan is crucial to improve the simulations of the model. We recently received a large data set that includes 10 years of observations of Holstein-Friesian cross bred and Zebu cattle. These data will also be used to test allocation rules for energy and protein in case of scarcity as this seems to be different between *Bos indicus* and *Bos taurus*. We plan to test thoroughly the growth and production routines of LIVSIM. We are planning also to improve the manure production routine to include more nutrients (P and K). Among the alternatives are to use the detailed model of Kebreab et al. (2002), or the detailed model of Dijkstra et al. (1996a; 1996b). A module on small ruminants, (goat and sheep) is another extension of LIVSIM that we are considering to implement.

**Acknowledgements**
To Agustine Ayantunde, Rob Delve and Andreas Jenet for providing data for the tests of the model. We thank Panos Konandreas for clarifying concepts from the model from which the main principles of LIVSIM were extracted. Henk Udo, Simon Oosting and Bill Thorpe were helpful in suggesting alternatives for the implementation of the intake function in the model, and suggesting relevant literature. Any error or omission in this document is the full responsibility of the authors.

# Appendix 2:
# Characterisation of the feeding strategies and cattle management in a Zimbabwean smallholder farming community [†]

## 1. Introduction

Beyond the natural variability of soil types across the landscape, the heterogeneity between farms is mainly driven by different management (Mtambanengwe and Mapfumo, 2006; Zingore et al., 2007). Livestock harvest and concentrate organic materials that may be further recycled for crop production. In the communal areas of NE Zimbabwe, the grazing area provides most of the feed for cattle during the rainy season, while crop residues support cattle during the dry season (Steinfeld, 1988). In the smallholder communal farming in NE Zimbabwe grazing land is considered a common property resource for the villagers. Herding only takes place during the cropping season. The official date of start of the cropping season is decided at the district level and constitutes a common reference for all villages within a district. At the village level, the head of the village, so called “kraal head”, is entitled to adapt dates according to the local situation. The head has the responsibilities to prevent misuse of the common land under his/her jurisdiction and to avoid overgrazing (Mutimukuru and Leeuwis, 2004). During the dry season, cattle freely graze crop residues left in the fields. The quantification of the effect of the practices on nutrient flows within the farming systems is important to identify adequate and promising strategies. The objective of this study was to describe different feeding and animal management practices to quantify nutrient transfers from grasslands to croplands and from the fields to the kraals of cattle owners. To achieve this, the study site was characterised by means of field observations, experiments and measurements, interviews of farmers, herders and key informants.

## 2. Material and methods

We selected a village in the communal area of Murewa, in NE Zimbabwe, in which we studied feed resources (natural grasslands and crop residues) and cattle animal and feeding management. Manjonjo consists of about 90 households located in two zones physically separated by a hilly woodland strip. Soils are predominantly sandy (Lixisols) with low fertility, with some areas of dolerite clay soils located in the hilly zones (Zingore et al., 2007b) (Fig. A31).

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[†] Extracted from:
Dury, J., Rufino M.C., M.T. Van Wijk, S. Zingore, M. Herrero, N. de Ridder and K.E. Giller. Feeding strategies and cattle mediated nutrient transfers in a maize-based Zimbabwean smallholder farming community, *in prep*

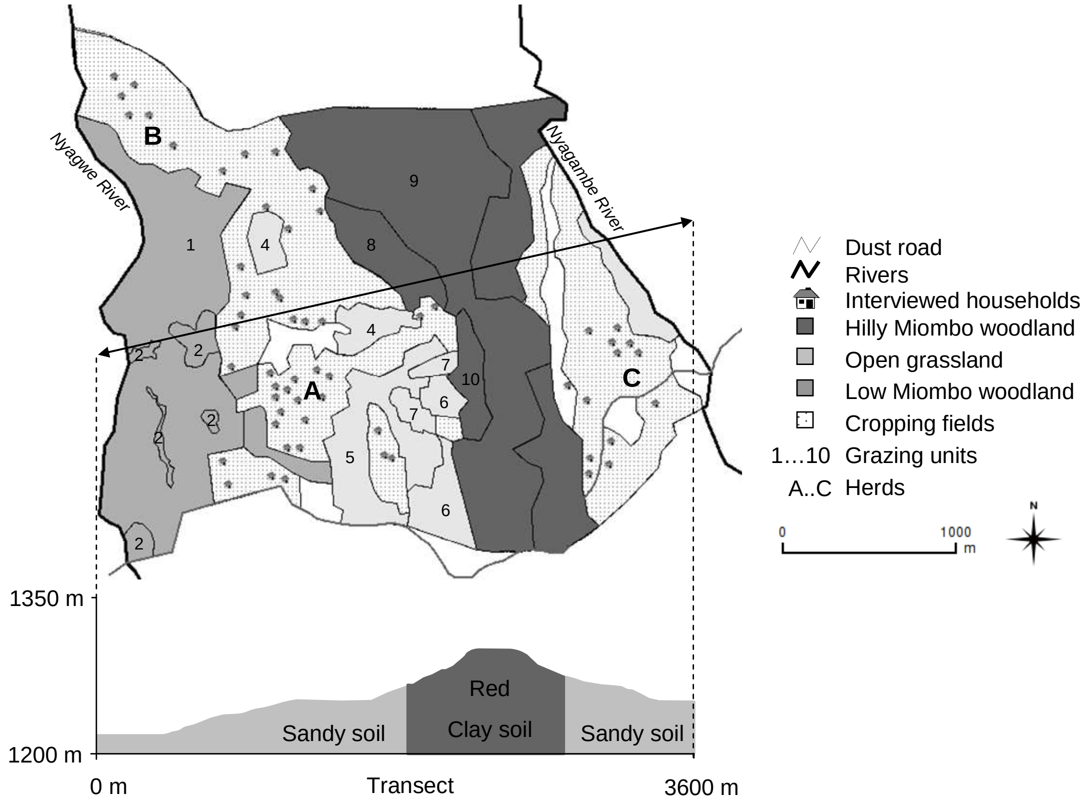


Figure A31: Village map with grazing unit locations from 1 to 10 and herd A, B and C location. The transect indicates the topography of Manjonjo with the corresponding soils.

### 2.1 Management practices

Two surveys were conducted, the first during the dry season of 2006, and the second during the rainy season of 2007. Data collection was carried out by conducting semi-structured interviews with farmers, non-structured interviews with key informants (e.g. the kraal head) and group meetings. All farm households owning cattle in Manjonjo (n = 37) and a group of randomly selected farm households who solely do cropping (n = 30) were interviewed. A simplified typology based on the wealth class was used similar to that of Zingore et al. (2007b) Information collected was summarized in four resource groups (RG).

### 2.2 Herd composition

Cattle census was carried out for the three herds of the village. The herds were defined as the group of animals that were herded together during the rainy season. Information was obtained from farmers to describe the herds in terms of breeds, bodyweight, and status of each individual. Cattle bodyweight measurements were taken for animals in the main herd in both dry and rainy season. Estimations of bodyweight were obtained by using an allometric relationship developed by Francis (2002) (Eq. 1) and direct measurements. Heart girth (HG) was preferred to other measurement because it is highly correlated with bodyweight (BW) (Francis et al., 2002).

$$BW = 73.11 - 1.96 \times HG + 0.02 \times HG^2 \quad \text{Eq. 1}$$

## 2.3 Feeding strategies

During the rainy season, cattle feed mainly in the communal grasslands. To understand the herding strategies, all 21 herders of the main herd were asked to indicate which areas of the grazing land were used during the rainy seasons of 2005/2006 and 2006/2007. Interviews took place in the evening when the herders returned to the village and were scattered during the three months of field work. Computation of GPS points together with an aerial photograph allowed the drawing of the map of Manjonjo and the calculation of grazing unit areas. The map was used as support for farmers to describe herding practices. Cattle tracks followed a day's grazing were drawn on a map of the grassland together with the herdsmen or were recorded with a GPS. The time spent by cattle in each different grazing unit identified by the herders was also recorded. The maps were complemented with a short semi-structured interview. The questionnaire focused on daily choices of grazing units, perceptions on grass quality and advantages and disadvantages of each grassland unit. Some herders were also accompanied during six days of duties to obtain better insight on herd management. During the dry season, cattle are not herded and graze freely, mainly on the crop residues in the cropland and they receive stored supplements of maize residues in the kraals. All the 37 cattle owners plus 30 crop farmers were interviewed about their crop residue management.

## 2.4 Quantification of the feed available in the grasslands

Three landscape units were defined, hilly Miombo woodland, open grassland and the low Miombo woodland, which differ in position in the landscape, tree density and soil types. Within these three landscape units other more detailed and homogeneous grazing units were defined based on the uses of the grassland by herders and on the waterlogging pattern. Dry standing biomass, litter and species composition of the grass strata were measured three times during the rainy season and once during the dry season at each of the grazing units. A destructive method was chosen to estimate standing aboveground biomass. The sample locations were randomly determined based on a predefined theoretical grid. A theoretical grid of ten locations was defined to cover all the area for each grazing unit. From these ten points, random numbers (for direction and distance) were used to define the sampling locations. The sampling method allowed sampling representative areas within each of the grazing units. The grasses were clipped in each quadrate of 1 $m^2$. All samples were spited into different species sub-samples. The species determination was carried out at beginning of March with the support of the National Herbarium and Botanic Garden of Zimbabwe. For all other measurements, the species composition was not carried out. The samples were oven-dried (70$^{o}$C) and weighted.

## 3. Results

### 3.1 Grassland characterisation and herding practices

We identified 10 grazing units across three landscape units on the basis on soil type, tree cover, water logging, land use and grazing intensity (Table A18). The biomass and the species composition observed were also strongly affected by the land use with a particularly strong effect of the grazing intensity (Table A19 and A20). Within Manjonjo, about 30% of the cattle belonged to 5 farmers of RG1, and 68% to 32 farmers of RG2. The herding patterns are described here at both temporal and spatial scales. According to the herdsmen, the seasonal herding pattern is determined by grass availability and accessibility to the different landscape units (Fig. A32). At the beginning of the cropping season, cattle were mainly herded in the open grassland characterised by the high quality of the new growth of the grasses and the open space. Furthermore, the close proximity of the crop fields to the open grassland allowed farmers to release their draught animals to join the herd after ploughing. As the rainy season progressed other units were included in the daily herding routes. The open grassland became too wet and too muddy, particularly in the vlei (grazing unit 5 and some part of grazing unit 4), thus limiting the grazing area and its accessibility. The low Miombo zone was the next zone which was preferred due to its large area and its proximity to the Nyagwe River. The hilly Miombo zone with numerous rocks, a steep slopes, tall vegetation and lack of a water point was referred by the herdsmen as the most difficult for herding. The general pattern of movement between grazing units for the late rain season is presented in Fig. A32 and the time spent per month at each unit derived from interviews and observations is presented in Fig. A33.

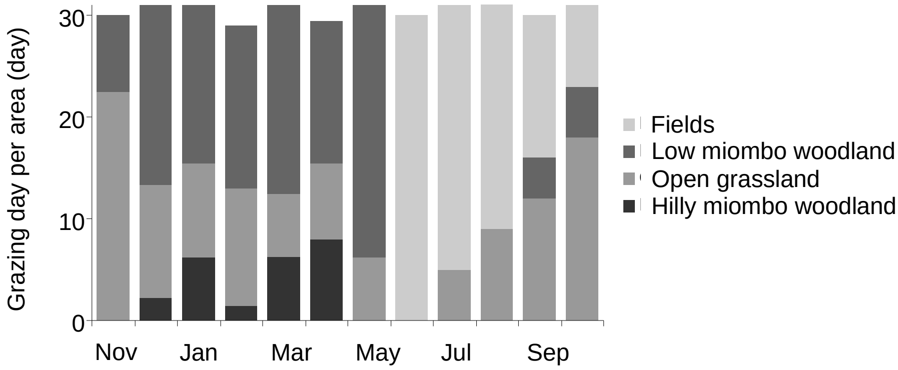


Figure A33: Monthly herding pattern across landscape units derived from herder interviews.

Table A18: Landscape units and characteristics of the grazing units, for the communal grassland of the Manjonjo village in NE Zimbabwe, Criteria for defining the grazing units were derived from observations and discussions with the herdsmen. Key species such as *Hyparrhenia dissoluta* and interviews about the herding pattern allowed defining the grazing intensity.

| Landscape unit | Grazing unit | Soil type | Tree cover | Water logging | Land use | Grazing intensity |
|---|---|---|---|---|---|---|
| Low Miombo woodland | 1 | Sandy | Young trees | No | Forest clearing | High |
| | 2 | Vlei | No trees | Yes | Grazing | Low |
| | 3 | Sandy | Young trees | Partial | Forest clearing | High |
| Open grassland | 4 | Sandy | No trees | No | Grazing | Low |
| | 5 | Vlei | No trees | Yes | Grazing | Low |
| | 6 | Sandy | No trees | No | Fallow | High |
| | 7 | Sandy | No trees | No | Fallow | High |
| High Miombo woodland | 8 | Red clay | Mature trees | No | Forest clearing | Low |
| | 9 | Red clay | Mature trees | No | Grazing | Very low |
| | 10 | Red clay | Mature trees | No | Forest clearing | Low |

Table A19: Characteristics of the grazing units of the communal grassland of the Manjonjo village in NE Zimbabwe. Area and standing biomass (kg ha$^{-1}$) and dead biomass (kg ha$^{-1}$) and criteria reported by the herdsmen to describe grazing unit advantages and constraints [+ refer to advantages; - refers to constraints]

| Landscape units | Grazing units | Area (ha) | March | | April | | May | | Grass quality | Field distance | Water-logged | View | Relief rocks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Stand. | Lit. | Stand. | Lit. | Stand | Lit. | | | | | |
| Low Miombo Woodland | 1 | 142 | 700 | 7 | 250 | 13 | 150 | 12 | --- | +++ | +++ | - | - |
| | 2 | 14 | 2400 | 288 | 2300 | 276 | 2100 | 441 | + | ++ | -- | + | +++ |
| | 3 | 11 | 330 | 3 | 2450 | 74 | 1900 | 19 | +++ | --- | - | ++ | +++ |
| Open Grassland | 4 | 17 | 2500 | 25 | 2350 | 141 | 2300 | 184 | + | --- | - | +++ | +++ |
| | 5 | 39 | 3300 | 132 | 3100 | 31 | 2900 | 435 | ++ | -- | --- | +++ | +++ |
| | 6 | 20 | 2000 | 0 | 1100 | 0 | 850 | 0 | ++ | - | +++ | +++ | +++ |
| | 7 | 8 | 1300 | 0 | 900 | 9 | 700 | 56 | + | - | +++ | +++ | +++ |
| High Miombo Woodland | 8 | 22 | 1550 | 78 | 1300 | 182 | 1200 | 288 | +++ | +++ | +++ | -- | -- |
| | 9 | 154 | 1050 | 179 | 800 | 248 | 600 | 264 | -- | +++ | +++ | --- | --- |
| | 10 | 12 | 1350 | 95 | 1000 | 190 | 900 | 243 | -- | +++ | +++ | --- | --- |

Table A20: Main species (% of the biomass) observed in March per landscape units.

| Species | Low Miombo woodland | Open grassland | High Miombo woodland |
|---|---|---|---|
| *Sporobolus pyramidalis* | 28 | 34 | <5 |
| *Hyparrhenia dissoluta* | 7 | 15 | 44 |
| *Andropogon gayanus* | <5 | <5 | 36 |
| *Aristida congesta* | 6 | <5 | <5 |
| *Heteropogon contortus* | <5 | <5 | <5 |
| *Cynodon dactylon* | <5 | <5 | <5 |
| *Digitaria gazensis* | <5 | <5 | <5 |
| *Cyperus* spp. | 10 | 17 | <1 |
| Mutsvairo* | 16 | <5 | <1 |

*Local name

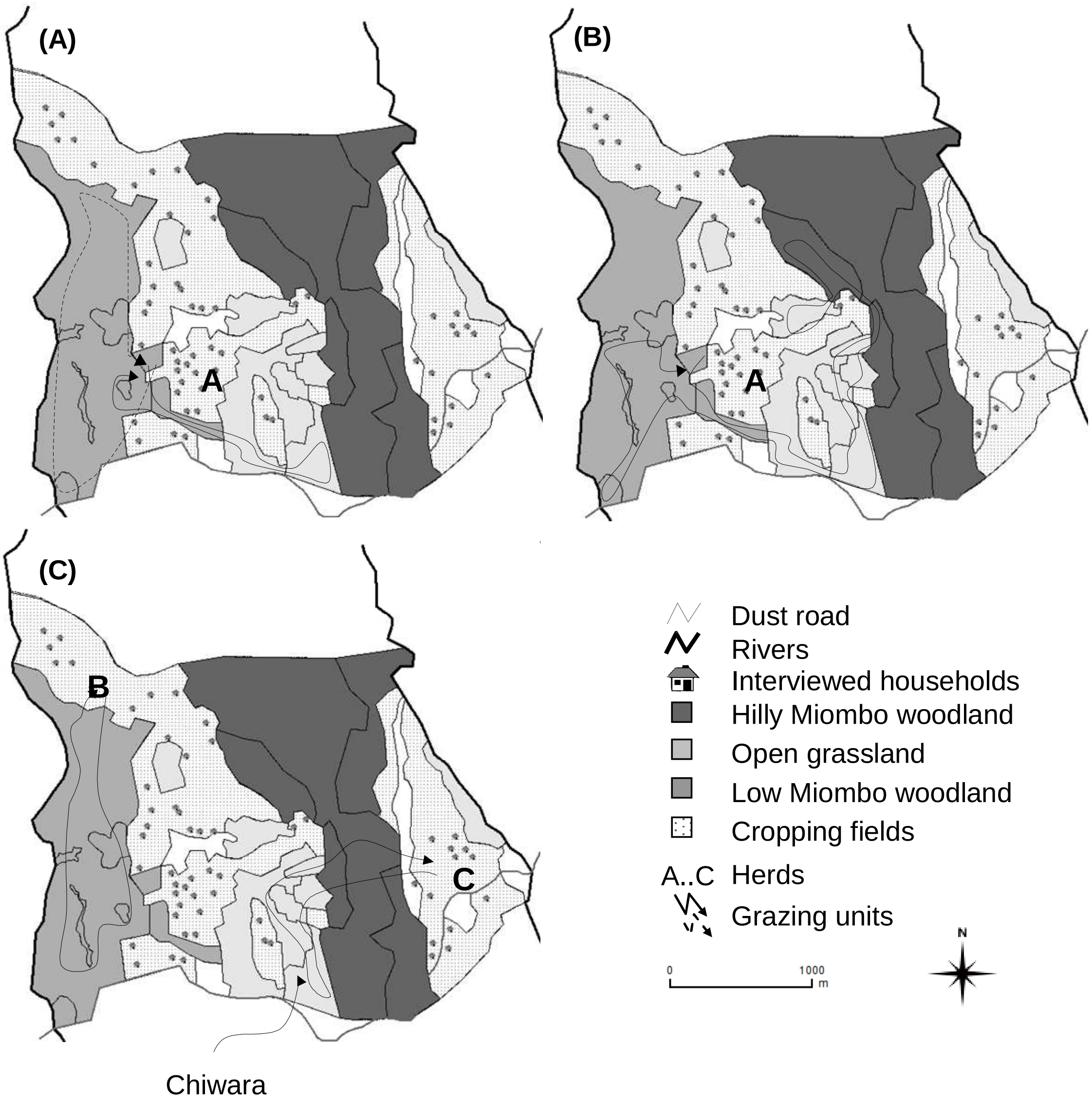


Figure A32: The map (A) shows two typical routes followed by herders of the main herd trying to reduce risk for cattle and the map (B) shows typical route for those trying to maximize feeding. The map C shows usual routes of the herds B, C from Manjonjo and of the herd from Chiwara.

The herding strategies also depend the herdsmen's own objectives. Two herder's objectives were identified: (i) reducing risk for cattle leg injuries by making herding easy, and (ii) optimising cattle feeding. The herdsmen's skills and the grazing area's characteristics acted as constraints to the achievement of the objectives. Herdsmen's skills are related to their age, experience in herding, and risk attitude. Characteristics of the grazing area mentioned by herders included herbage biomass, topography, visibility, crop field proximity and presence or absence of natural barriers. The two emerging herding strategies are illustrated in Fig. A32B and C by what were (typical) tracks followed by herders. About 53% of the interviewed herders were younger than 16 years. For 71% of them, their first objective was to bring back the cattle safely to their owners without any problems; others reported searching the best grasses for cattle as the main objective. In contrast, 66% of the adult herdsmen – mostly cattle owners, had leading the cattle to the best feeding places as the main objective for herding.

The objectives strongly affected herding patterns for both young and adult herders as illustrated Figs A32B and C. The herders trying to minimise risk and to bring back cattle safely clearly preferred grazing units 1 and 6. These large areas with relatively flat topography and the presence of natural barriers, the Nyagwe River for grazing unit 1 and the hilly forest for grazing unit 6, made herding easier than in other grazing units. The drawback of these relatively safe areas compromising is the low herbage biomass in these units. The herders with feed quality as main objective had more diverse herding patterns and followed more complex tracks within the grazing units. When herders looked for grass, they herded the cattle through areas with high standing biomass. While both groups spent the same amount of time within the low Miombo woodland (about 70% of the in time), herders that tried to maximise cattle feeding spent much more time in grazing unit 2 than in others. Keeping cattle within grazing unit 2 required much more attention, since this unit is composed of small areas embedded within grazing unit 1. Accessibility of some areas (e.g. grazing unit 4 and 8) was more difficult and often required going close to the cropping fields and therefore increased the risks of cattle damaging crops. The grazing unit 8 located within the hilly Miombo woodland is scattered with numerous rocks which increases the risk of cattle leg injuries. Only good and skilled herders went into this unit. The grazing unit 4 was often used during the middle of the day as herders were close to their homes and could go there for lunch.

## 3.2 Crop residue production and uses

Different and often competing uses of crop residues co-existed within the different resource groups. Farmer's objectives, perceptions on the value of the crop residues and labour required were identified to be the three main determinants for the decisions made by farmers with regard to the use of crop residues. There were clear differences in management strategies between resource groups. Almost all cattle owners (RG1 and RG2) reported that they collect the crop residues, which was not the case for crop farmers (RG3 and RG4) where practices were much more diverse. In total, 66% of the interviewed farmers reported some crop residue management practices after the harvest of the grain. Collection was the most common practice, burning and incorporating into soil by ploughing were the two others. Only three farmers reported that they burn the crop residues within the fields. The main motivation for burning residues was to prevent cattle from grazing in their fields and also to keep the fields clean. Farmers who did not have any specific management practices for the crop residues represented 44% of all farm households. Their overall crop residue production of maize stover represented 27% of the total production of all farmers together. Reported reasons for not using residues were different between cattle owners and non-cattle farmers. The cattle owners were not interested in collecting residues since the cattle can freely access them while grazing. Non-cattle farmers had two reasons for not managing the crop residues: i) The time and effort required for collecting residues were reported as the main reason for 50% of households; and ii) 40% of the farmers preferred to allow the cattle to graze their fields in order to obtain benefits from the manure excreted by the grazing cattle. Another 10% mentioned reasons such as termites that consume the residues during the composting process and the rest did not give any specific reasons for not collecting the crop residues.

# Appendix 3:
# Quality parameters of the grass and legume species used in the simulations of Chapter 7

Table A21: Main feed quality parameters for the main grass species used in all the simulations and the legumes used in the supplementation scenario.

| | Early rainy season | | | Early dry season | | | Late dry season | | |
|---|---|---|---|---|---|---|---|---|---|
| Grass species | ME (MJ kg DM$^{-1}$) | DMD (g kg DM$^{-1}$) | CP (g kg DM$^{-1}$) | ME (MJ kg DM$^{-1}$) | DMD (g kg DM$^{-1}$) | CP (g kg DM$^{-1}$) | ME (MJ kg DM$^{-1}$) | DMD (g kg DM$^{-1}$) | CP (g kg DM$^{-1}$) |
| *Hyparrhenia dissoluta* | 10.2 | 650 | 135 | 8.0 | 510 | 45 | 6.3 | 400 | 40 |
| *Sporobolus pyramidalis* | 9.8 | 620 | 125 | 7.9 | 400 | 43 | 5.2 | 330 | 30 |
| *Heteropogon contortus* | 10.5 | 670 | 110 | 7.5 | 410 | 32 | 5.8 | 370 | 24 |
| *Digitaria gazensis* | 11.5 | 700 | 163 | 9.2 | 630 | 74 | 8.2 | 530 | 45 |
| *Andropogon gayanus* | 9.7 | 620 | 158 | 8.0 | 470 | 58 | 6.2 | 400 | 47 |
| *Cynodon dactylon* | 10.4 | 640 | 137 | 8.3 | 517 | 60 | 8.0 | 500 | 50 |
| *Aristida congesta* | 10.0 | 650 | 109 | 7.8 | 420 | 52 | 5.8 | 370 | 43 |
| Other feeds | | | | | | | | | |
| *Leucaena leucocephala* | - | - | - | 9.7 | 720 | 252 | - | - | - |
| *Zea mays* stem | - | - | - | 8.0 | 520 | 72 | 7.6 | 500 | 50 |
| *Zea mays* leaves | - | - | - | 6.8 | 500 | 54 | 6.0 | 450 | 45 |

Sources: Topps and Oliver (1993), Boudet (1991), DYNAFEED – ILRI Feed database.


Figure A34: Example of the simulated total grass biomass production in three different landscape units: low Miombo woodland, open grassland, and high Miombo woodland at the grassland of the virtual village, using the average rainfall series.

# Summary

Smallholder farming systems in Sub-Saharan Africa are often nutrient-limited systems that depend largely on the use of land resources for their subsistence. It is often stated that crop-livestock integration is an effective means by which plant nutrients can be rapidly recycled within and between farms. However, there is great uncertainty on which are the critical stages of nutrient transfer through crop-livestock systems. Each transfer of nutrients within the farming system provides a risk of inefficiency, and how much is lost at each step depends on the type system, its management practices and site conditions. Farmers in Africa recognise the important role of manure in maintaining soil fertility. The poorest smallholders may benefit from integrating livestock with crops because of the reduction of vulnerability to risk (through the insurance function of livestock), and because of the opportunities created for recycling and maintaining soil productivity. Because livestock fulfil several functions in crop-livestock systems, farmers manage their animals according to the weight assigned to each function. As a consequence there are trade-offs between increasing animal productivity, income from livestock and sustaining crop production through cycling nutrients from animal manure. This thesis is a contribution to development of a analytical tool, the NUANCES framework, to support the analysis of trade-offs in crop-livestock systems, with focus on opportunities for intensification and maximising the benefits from crop-livestock integration for smallholder farmers. To address this objective, examples from different mixed crop-livestock systems, a combination of qualitative (participatory research, farm typologies) and quantitative system analytical methods (experiments and modelling) were used.

Farming systems were conceptualised in four sub-systems through which nitrogen (N) transfer takes place: 1. Livestock: animals partition dietary intake into growth and milk production, faeces and urine; 2. Manure collection and handling: housing and management determine what proportion of the animal excreta may be collected; 3. Manure storage: manure can be composted with or without addition of plant materials; 4. Soil and crop conversion: a proportion of the N in organic materials applied to soil becomes available, part of which is taken up by plants, of which a further proportion is partitioned into grain N. Critical steps where efficiency of nitrogen (N) cycling through livestock in African smallholder crop-livestock farming systems can be increased were identified (Chapter 2). Partial efficiencies have been more commonly reported in the literature for the first and last steps than for manure handling and

storage. N cycling efficiencies are calculated for every sub-system as the ratio of nutrient output to nutrient input. Estimates of this so-called partial N cycling efficiency (NCE) for each sub-system range from 46–121 % (Livestock), 6–99 % (Manure handling), 30–87 % (Manure storage) and 3–76 % (Soil and crop conversion). Overall N cycling efficiency is the product of the partial efficiencies at each of the steps through which N passes. Direct application of plant materials to soil results in more efficient cycling of N, with fewer losses than from materials fed to livestock. However, livestock provide many other benefits highly valued by farmers, and animal manures can contain large amounts of available N which increases crop responses. Making most efficient use of animal manures depends critically on improving manure handling and storage, and on synchrony of mineralisation with crop uptake. Measures to improve manure handling and storage are generally easier to design and implement than measures to improve crop recovery of N.

For smallholder farmers who use little fertiliser, efficient nutrient management in manure is key for crop production. A model (HEAPSIM) was developed to analyse NCE within smallholder farms in western Kenya (Chapter 3). The model was built with on-farm data on manure excreted and manure management in combination with experimental results and literature to analyse losses during manure storage. The model calculations show that manure management during collection and storage has a large effect on the efficiency of mass and nutrient retention. Differences in NCE between farms of different wealth classes arise due to differences in resource endowment. For poorer farmers, larger N losses occur at all stages of manure cycling compared to the wealthier farms. Urinary-N losses occur on all farms but their impact on NCE for poor and medium-class farmers is larger due to the smaller amount of N recycled. With current management the poor farmer recover <1 kg N $y^{-1}$ in composted manure from 15 kg N $y^{-1}$ excreted. Improved manure storage has little effect on increasing overall NCE for the poor farmer due to large losses during collection. For the wealthier farmer, improvement of manure storage increases NCE and allows recycling of 30% of N excreted (ca. 30 kg N $y^{-1}$) with small investment in infrastructure. Increasing cattle numbers or improved feeding would have a larger effect on manure availability but this is constrained by feed scarcity and investment capacity. The absolute amounts of N recycled (1−6, 4−17 and 7−18 kg N $y^{-1}$ for poor, medium and wealthier farmers) are small compared with maize N demand (>50 kg N $ha^{-1}$), but significant to farmers given the small farm sizes (0.1 – 1.1 ha). Besides N, animal manure provides other nutrients for crops and maintains soil organic matter –both vital to guarantee efficient use of fertiliser N – which justifies the search for interventions to assist farmers make better use of manure. Covering manure heaps with a polythene film reduce mass and N losses considerably. To increase overall NCE, investment in cattle housing and recycling of urinary-N is required.

Evaluation of the cows' lifetime productivity is a sensible strategy to target interventions to improve productivity of smallholder dairy systems in the highlands of East Africa. Feeding strategies and mortality may have a long-term effect on productive (and therefore economic) performance of dairy systems (Chapter 4). Because of the temporal scale needed to evaluate lifetime productivity (more than 10 years in dairy systems of the Highlands of East Africa), experimentation with feedstuffs in single lactations is not enough to assess productive improvements. A dynamic modelling approach was used to explore the effect of feeding strategies on dairy cattle lifetime productivity, and to help to identify entry points where interventions will have a productive impact. In the individual-based dynamic model LIVSIM-(Livestock Simulator), animal production depends on genetic potential of the breed and feeding. We simulated individual animals throughout their lifetime using scenarios with different diets based on common feedstuffs used in these systems (Napier grass, maize stovers and dairy concentrates), with and without imposing random mortality rates to different age classes. The simulations show that it is possible to target the feeding to maximise lifetime productivity by supplementing with concentrates to meet the nutritive requirements of cattle not only during lactation, but also during early development to reduce age at first calving and extend productive lifetime. Avoiding undernutrition during the dry period by supplementing the diet with 0.5 kg of dairy concentrates increases productivity and productive lifetime. Survival analyses indicate that non-supplemented diets prolong calving intervals. The simulations with imposed random mortality show a reduction in productive life, number of calvings and therefore all other productivity indicators by about 43−65%. Selecting the best feeding strategies makes little sense when mortality of cattle may be as high as 15% per year. Therefore, reducing mortality by implementing health care management programmes must be included in interventions to increase dairy outputs. Improving lifetime productivity is more effective than interventions targeted to improving daily milk yields through feeding strategies.

Diversity of farming activities may increase the stability of the production of the farm and reduce risks for resource-poor households, whereas integration of activities using the outputs of one activity as input in another activity may reduce dependency on external resources (Chapter 5). In practice, diversity and integration are poorly defined and there is no method to assess diversity and integration in agro-ecosystems, which hampers the exploration of their potential benefits. A method based on Network

Analysis (NA) is introduced to characterize and assess the diversity and integration in farm household systems. The Finn's Cycling index (FCI) is used to characterise the degree of integration of farming activities. Diversity is characterised by using measures of communication theory − the Average Mutual Information (AMI) and its upper boundary the statistical uncertainty ($H_R$). The method is applied to mixed crop-livestock systems of the Highlands of Northern Ethiopia where we used nitrogen (N) flows to illustrate the utility of the method. The indicators are useful to support discussions on diversified and sustainable agro-ecosystems and allow assessment of the effects of different farm management to improve the system design. The definition of the agro-ecosystem and its compartments (farming activities) and scales strongly affect the outcomes of the evaluations. The potential of NA for drawing recommendations on sustainable management depends on proper systems definitions and the objectives of study.

Because many farmers in Sub-Saharan African rely on the use of natural resources, the inflows of nutrients to the systems should be increased to compensate for exports and losses, while increased integration through internal cycling may increase the efficiency of nutrient utilisation. To explore to what extent the properties of nutrient cycling networks relate to the capacity of the systems to sustain rural families, we investigated the characteristics of N flows and cycling in contrasting African crop-livestock systems by using concepts form ecological network analysis (NA) (Chapter 6). The case studies included farm households from different social strata at three sites: Tigray in northern Ethiopia, Kakamega in western Kenya and Murewa in Zimbabwe. These farm households were conceptualised as networks, in which the the household and the different farming activities represent the compartments, and the N flows were the connections between them. Indicators were used to assess network size, activity and cycling, and the organisation and diversity of the N flows which were compared to measures of system performance (biomass productivity and food self-sufficiency). Systems in Tigray used about three times more N per capita than the systems in Kakamega, with Murewa in between. The amounts of N cycled were small and comparable at all sites (less than 2.5 kg N *per capita* per year). Dependency on external inputs to sustain current production was larger for poor than for wealthier households, who had larger soil N storages per capita. Poor households did not achieve food self-sufficiency at any of the three sites. The measures of system performance were positively related to the size of the network of N flows and to the organisation and cycling, but the efficiencies of utilisation were different across the sites in relation to the size of soil storages and the importance of livestock to the N flows of the system. This use of NA appears promising to assess systems agro-ecosystems properties by looking at dependency on the external environment for biophysical inputs and the internal organisation of the system. Because increases in size of the network of N flows and organisation of the flows lead to increases in productivity and food self-sufficiency, combination of both strategies may benefit not only productivity but also adaptability and reliability of smallholders crop-livestock systems.

Addition of organic materials is needed to sustain the crop productivity of inherently poor soils in the mixed crop-livestock systems of the communal areas of North East Zimbabwe. In these systems, livestock feed resources are collectively managed, with the herds of the village grazing on natural grasslands during the rainy season and on crop residues during the dry season. This creates different types of interactions between the members of the community, livestock owners *vs* non-livestock owners, including competition for the organic resources. The magnitude of such interactions in terms of nutrient flows and the long term effects of the current practices on soil productivity is explored (Chapter 7). It is hypothesised that the collective management of feed resources brings negative consequences for non-livestock owners. We used information on crop and livestock management collected in a village of the communal area of Murewa in NE Zimbabwe, and a dynamic farm-scale simulation model (NUANCES-FARMSIM). The individual models of FARMSIM have been calibrated and tested with existing information for the same area, and adapted to include the main interactions at village scale. The simulations of 10 years showed that the grasslands contributed the majority of the annual feed intake of the herd of the village, (c. 75%), and that the crop residues produced by the non-livestock owners sustained a substantial (c. 30%) amount of the intake of livestock during the critical dry season. The removal of C ( 0.3−0.4 t C $y^{-1}$) from their fields resulted in a long term reduction of the already poor yields of their farms. Impeding the access of livestock to the crop residues of non-livestock owners increased the quality of their soils modestly and improved yields in the mid- to long term, but not enough to meet the needs of the family. Although our hypothesis was not rejected, the negative effects were relatively small. Adding inputs to the whole (community) system in the form of mineral fertiliser concurrently with changes to the current management of the crop residues and manures by redistributing manure from the more fertile fields of the farm to the poorer soils, appears to be a promising strategy to boost the productivity of the community as a whole. The likelihood of this scenario being implemented depends on the availability of fertilisers and the willingness of farmers to invest in rehabilitating soils to obtain benefits in the long term, as opposed to concentrating all organic inputs in small areas and creating islands of fertility where crop yields are secured.

There are benefits in terms of productivity and resource use efficiency of closer integration between crops and livestock. Some of these benefits are to be obtained with relatively small technical changes and others need to be combined with radical institutional changes and/or system shifts.

# Samenvatting

Kleine boerenbedrijven in Afrika ten zuiden van de Sahara zijn vaak nutriënt-gelimiteerde systemen, die grotendeels afhankelijk zijn van het gebruik van het beschikbare land voor hun bestaan. Er is vaak gezegd dat integratie tussen gewas en vee een effectieve manier is waarop plant nutriënten snel hergebruikt kunnen worden, zowel binnen een boerderij als tussen meerdere boerderijen. Er is echter grote onzekerheid over de kritische momenten van nutriënt overdracht in gemengde gewas-vee systemen. Elke overdracht van nutriënten binnen een boerderij systeem vormt een risico van inefficiëntie, en hoeveel verloren gaat bij iedere stap hangt af van het type systeem, het toegepaste beheer en de locale condities. Boeren in Afrika onderkennen de belangrijke rol die dierlijke mest speelt in het behoud van bodemvruchtbaarheid. De armste kleine boeren kunnen mogelijk profiteren van de integratie van vee met gewassen vanwege de reductie van hun kwetsbaarheid voor risico’s (door middel van de bufferfunctie van vee), en vanwege de mogelijkheden die gecreëerd worden voor hergebruik en het op peil houden van de bodemproductiviteit. Omdat vee verschillende functies in gemengde bedrijven vervult, beheren boeren hun vee op een manier die aansluit bij welke zij van die functies de belangrijksten vinden. Als gevolg hiervan zijn er trade-offs tussen het laten toenemen van de dierlijke productie, het inkomen dat gegeneerd wordt door het vee en het behoud van gewasproductie door middel van het hergebruik van nutriënten van dierlijke mest. Deze thesis vormt een bijdrage aan de ontwikkeling van een analytisch gereedschap, het NUANCES systeem, welke gebruikt wordt om de analyse van trade-offs in gemengde gewas-vee systemen te ondersteunen, met een focus op de mogelijkheden voor intensificatie en de maximalisatie van de voordelen van gewas-vee integratie voor kleine boeren. Om deze doelstelling te bereiken zijn voorbeelden van verschillende gemengde gewas-vee systemen, een combinatie van kwalitatieve (participatief onderzoek, bedrijfstypologieën) en kwantitatieve systeem-analytische methoden (experimenten en simulatiemodellen) gebruikt.

Boerderijsystemen zijn geconceptualiseerd in 4 subsystemen waar nutriënten doorheen stromen: 1. Het vee: dieren verdelen hun voerinname over groei, melkproductie, mest en urine; 2. Dierlijke mestverzameling en beheer: het type opslag en het beheer bepalen welk deel van de dierlijke uitwerpselen kunnen worden gebruikt; 3. Mestopslag: mest kan gecomposteerd worden met of zonder toevoeging van plantaardige materialen; 4. Bodem en gewasconversie: een gedeelte van de stikstof (N) in organisch materiaal dat aan de bodem wordt toegevoegd komt beschikbaar, waarvan weer een gedeelte door de planten wordt opgenomen, waarvan weer een gedeelte uiteindelijk

terecht komt in het graan. Belangrijke stappen, waar de efficiëntie van N hergebruik door vee in Afrikaanse kleine gemengde boerenbedrijven kan worden verbeterd, werden geïdentificeerd (Hoofdstuk 2). Partiële efficiënties zijn vaker berekend voor de eerste en de laatste stappen dan voor het beheer van de mest en de opslag ervan. N gebruiksefficiënties zijn berekend voor elk subsysteem als de ratio tussen nutriënt output en nutriënt input. Schattingen van deze zogenaamde partiële N gebruiksefficiënties (Nutrient Conversion Efficiencies - NCE) variëren voor elk subsysteem tussen 46 tot 121% (vee), 6 tot 99% (mestbeheer), 30 tot 87 % (mestopslag) en 3 tot 76% (bodem- en gewasconversie). De gehele N gebruiksefficiëntie is het product van de partiële deficiënties van elke stap waar N doorheen gaat. Directe toepassing van plantaardige materialen op de bodem leidt tot een meer efficiënt gebruik van N, met lagere verliezen dan wanneer het materiaal aan het vee wordt gevoerd. Vee geeft echter andere voordelen die hogelijk gewaardeerd worden door boeren, en dierlijke mest kan grote hoeveelheden beschikbare N bevatten die de gewasrespons verbeteren. Het meest efficiënte gebruik van dierlijke mest hangt kritisch af van het verbeteren van het beheer en de opslag van de dierlijke mest, en van de synchronisatie van mineralisatie met de opname van gewassen. Maatregelen om het beheer en de opslag van de dierlijke mest te verbeteren zijn eenvoudiger te ontwerpen en toe te passen dan maatregelen om de opname efficiëntie van gewassen te verbeteren.

Voor kleine boeren, die weinig kunstmest gebruiken, is efficiënt beheer van nutriënten essentieel voor de gewasproductie. Een simulatiemodel (HEAPSIM) werd ontwikkeld om de NCE van kleine boerenbedrijven in West Kenia te analyseren (Hoofdstuk 3). Het model werd gebouwd met behulp van bedrijfsgegevens op het gebied van mestproductie en mestbeheer in combinatie met experimentele resultaten en literatuurgegevens en werd gebruikt om de verliezen tijdens mestopslag te analyseren. De modelsimulaties lieten zien dat het type beheer van mest gedurende de verzameling en opslag een groot effect had op efficiëntie van het behoud van koolstof (C) en nutriënten in de mest. Verschillen in NCE tussen boerderijen in verschillende klassen van rijkdom ontstonden door verschillen in het bezit van beschikbare middelen. Bij de arme boeren traden, vergeleken met de rijkere boeren, grote N verliezen op bij alle stappen van mestgebruik. N verliezen in urine vonden plaats op alle bedrijven, maar hun effect op NCE was groter voor arme en gemiddeld rijke boeren omdat de totale hoeveelheid N dat hergebruikt word op deze bedrijven kleiner is. Met het huidige beheer gebruiken boeren minder dan 1 kg N per jaar ten opzichte van 15 kg N dat per jaar in de uitwerpselen geproduceerd wordt. Verbeterde mestopslag heeft een klein effect op het laten toenemen van de NCE voor de arme boeren omdat grote verliezen optreden tijdens het verzamelen. Voor de rijkere boeren leidt een verbetering van de mestopslag tot een verhoogde NCE en maakt het mogelijk om 30% van N in dierlijke mest (ongeveer 30 kg N per jaar) te hergebruiken met een kleine investering in type opslag. Een toename in hoeveelheid vee of een verbetering in het voer zou een groter effect hebben op de beschikbaarheid van mest, maar dit wordt beperkt door de mogelijkheden voor investeringen en de schaarsheid van voer. De absolute hoeveelheden van hergebruikte N (1–6, 4–17 and 7–18 kg N per jaar voor arme, gemiddelde and rijkere boeren, respectievelijk) zijn klein vergeleken met de vraag naar N door het gewas maïs (meer dan 50 kg per ha). Naast N geeft dierlijke mest ook andere nutriënten voor gewassen en het levert een bijdrage aan het behoud van bodem organisch materiaal – allebei essentieel om efficiënt gebruik van kunstmest N te garanderen – waardoor het zoeken naar interventies om boeren te ondersteunen om beter gebruik te maken van mest nuttig blijft. Het bedekken van een mesthoop met plastic vermindert de massa en N verliezen aanzienlijk. Om de totale NCE te verhogen is investering in veestalling en het hergebruik van urine N noodzakelijk.

Evaluatie van de levensproductiviteit van vee is een logische strategie om toegespitste interventies om de productiviteit van kleine melkveebedrijven in de hooglanden van Oost Afrika te verhogen te kunnen identificeren. Voerstrategieën en mortaliteit kunnen een lange termijn effect hebben op productiviteit (zowel dierlijk als economisch) van melkveebedrijven (Hoofdstuk 4). Vanwege de tijdsschaal die nodig is om de levensproductiviteit te kunnen evalueren (meer dan 10 jaar in melkveesystemen in de hooglanden van Oost Afrika), zijn experimenten met verschillende typen voer in een enkele lactatie niet genoeg om productiviteitsverbeteringen te kunnen evalueren. Een dynamische simulatie aanpak is gebruikt om het effect van voerstrategieën op de levensproductiviteit van melkvee te onderzoeken en om momenten te kunnen identificeren waar interventies een impact kunnen hebben op de productiviteit. In het individueel-gebaseerde simulatiemodel LIVSIM (LIVestock SIMulator) hangt dierlijke productie af van het genetische potentieel van het ras en het voer. We simuleerden individuele dieren gedurende hun leven, daarbij gebruikmakend van scenario's met verschillende diëten welke gebaseerd waren op de gebruikelijke typen voer beschikbaar in deze systemen (Napier gras, maïsresiduen en krachtvoer), samen met het wel of niet toepassen van een random kans op mortaliteit voor de verschillende ouderdomsklassen. De simulaties lieten zien dat het mogelijk is het voer dusdanig aan te passen dat de levensproductiviteit gemaximaliseerd kan worden door het gebruik van krachtvoer om aan de vraag naar energie en eiwitten van het vee te voldoen, niet alleen gedurende lactatie maar ook gedurende de vroege ontwikkeling om de leeftijd bij het krijgen van het eerste kalf te verlagen en om het productieve leven te verlengen. Het voorkomen van ondervoeding gedurende de droge periode door het bijvoeren van 0.5 kg krachtvoer vergrootte de productiviteit en het productieve leven. Overlevingsanalyses lieten zien dat diëten zonder bijvoeding het kalfinterval verlengden. De simulaties met een random kans op mortaliteit lieten een verkorting zien van het productieve leven en een verlaging van het aantal kalveren, en daarmee ook in alle andere indicatoren van productiviteit, met ongeveer 43 tot 65%. Het selecteren van de beste voerstrategie is niet effectief wanneer de mortaliteit van vee zo hoog is als 15% per jaar. Het reduceren van mortaliteit door het implementeren van gezondheidsprogramma's moet daarom meegenomen worden in interventies om de melkproductie te verhogen. Het verhogen van de levensproductiviteit is effectiever dan interventies gericht op het verbeteren van melkproductie met behulp van verbeterde voerstrategieën.

De diversiteit van activiteiten op een boerderij kan de stabiliteit van productie op het bedrijf positief beïnvloeden en kan de risico's voor arme huishoudens verminderen, terwijl de integratie van activiteiten waarin de output van de ene activiteit gebruikt wordt als input voor een andere activiteit de afhankelijkheid van externe bronnen kan reduceren (Hoofdstuk 5). In de praktijk zijn diversiteit en integratie slecht gedefinieerd en er bestaat geen methode om de diversiteit en integratie van agro-ecosystemen te evalueren. Dit limiteert de verkenning van hun mogelijke voordelen. Ik introduceer een methode die gebaseerd is op Netwerk Analyse (NA) om de diversiteit en integratie van boerderij systemen te karakteriseren en te evalueren. De Finn HergebruiksIndex (Finn's Cycling Index - FCI) is gebruikt om de mate van integratie van boerderij activiteiten te karakteriseren. Diversiteit wordt gekarakteriseerd met behulp van methoden uit de communicatie wetenschappen – de Gemiddelde Wederzijdse Informatie (Average Mutual Information – AMI) and de bijbehorende bovengrens van de statistische onzekerheid ($H_R$). De methode is toegepast op gemengde gewas-vee systemen van de hooglanden van Noord-Ethiopië. We gebruikten N stromen om het nut van de methode te laten zien. De indicatoren zijn nuttig om discussies over diverse en duurzame agro-ecosystemen te ondersteunen en om de evaluatie te ondersteunen van effecten van verschillende typen boerderij beheer, om hiermee het beter mogelijk te maken om nieuwe boerderijsystemen te ontwerpen. De definitie van het agro-ecosysteem en zijn compartimenten (de boerderij activiteiten) samen met de niveaus van analyse beïnvloeden de uitkomsten van de evaluaties sterk. Het potentieel van NA om aanbevelingen te identificeren op het gebied van duurzaam beheer hangt af van correcte systeem definities en de doelstelling van de desbetreffende studie.

Omdat veel boeren in Afrika ten zuiden van de Sahara afhankelijk zijn van het gebruik van natuurlijke bronnen, moeten de stromen van nutriënten naar de systemen toenemen om te compenseren voor de export en het verlies van nutriënten, terwijl een sterkere integratie door intern hergebruik de efficiëntie van nutriënt gebruik kan verhogen. Om te bekijken in welke mate de eigenschappen van netwerken van nutriënt hergebruik gerelateerd kunnen worden aan de capaciteit van systemen om rurale families te onderhouden, onderzochten we de karakteristieken van N stromen en N hergebruik in contrasterende Afrikaanse gewas-vee systemen met behulp van concepten van de ecologische netwerk analyse (NA) (Hoofdstuk 6). De locaties die onderzocht werden bevatten boerenhuishoudens van verschillende sociale niveaus in drie verschillende regio's: Tigray in Noord Ethiopië, Kakamega in West Kenia en Murewa in Zimbabwe. Deze huishoudens werden geconceptualiseerd als netwerken waarin de huishoudens en de verschillende boerderij activiteiten de compartimenten representeren, en de N stromen waren de connecties tussen hen. Indicatoren werden gebruikt om de grootte van het netwerk te evalueren. De activiteit en mate van hergebruik samen met de organisatie en diversiteit van de N stromen werden vergeleken met maten van system productiviteit (biomassa productie en voedselzelfvoorziening). De systemen in Tigray gebruikten ongeveer 3 maal meer N per persoon in het huishouden dan de systemen in Kakamega, terwijl Murewa er tussenin zat. De hoeveelheden van hergebruikte N waren klein en vergelijkbaar tussen alle locaties (minder dan 2.5 kg N per persoon per jaar). De afhankelijkheid van externe inputs om de huidige productie te behouden was groter voor de arme dan voor de rijkere huishoudens, deze laatsten hadden meer N voorraad per persoon. Arme huishoudens bereikten in geen van de locaties voedselzelfvoorziening. De maten die gebruikt werden om de de productiviteit van het systeem te karakteriseren waren positief gerelateerd aan de grootte van het netwerk van N stromen en aan de organisatie en het hergebruik, maar de efficiënties van gebruik waren verschillend tussen de locaties in relatie tot de grootte van de bodemvoorraad en het belang van het vee voor de N stromen in het systeem. Dit gebruik van NA lijkt veelbelovend om eigenschappen van agro-ecologische systemen te evalueren door te kijken naar de afhankelijkheid van de omgeving voor biofysische inputs en de interne organisatie van het systeem. Omdat toename van de grootte van het netwerk van N stromen en de organisatie van deze stromen leiden tot toenames in de productiviteit en voedselzelfvoorziening, kan de combinatie van beide strategieën leiden tot een hogere adaptiviteit en betrouwbaarheid van kleine gemengde gewas-vee bedrijven.

Toepassing van organisch materiaal is noodzakelijk om de gewasproductie te behouden op inherent arme gronden in gemengde gewas-vee systemen in Noordoost Zimbabwe. In deze systemen wordt het voer voor het vee gemeenschappelijk beheerd, waarbij de kuddes van de het dorp grazen op natuurlijke graslanden gedurende het regenseizoen en op gewasresiduen gedurende het droge seizoen. Dit zorgt voor verschillende typen van interacties tussen de individuen van de locale gemeenschap, de boeren die wel of geen vee in hun bezit hebben, waarbij ook concurrentie plaatsvindt om de beschikbare organische bronnen. De grootte van deze interacties in termen van nutriëntstromen en de lange termijn effecten van de huidige praktijk in termen van bodemproductiviteit zijn onderzocht (Hoofdstuk 7). De hypothese was dat het gemeenschappelijke beheer van beschikbaar voer negatieve consequenties heeft voor de boeren zonder vee. We gebruikten informatie over het beheer van de gewassen en het vee, verzameld in een dorp in Murewa in Noordoost Zimbabwe, samen met een dynamisch simulatiemodel oorspronkelijk ontwikkeld op boerderij niveau (NUANCES-FARMSIM). De individuele modules van FARMSIM zijn gekalibreerd en getest met behulp van bestaande informatie van hetzelfde gebied, en aangepast om de belangrijkste interacties op dorpsniveau te kunnen beschrijven. De simulatie van 10 jaar liet zien dat de graslanden zorgen voor het belangrijkste deel van de voeropname van de dorpskudde (ongeveer 75%) en dat de gewasresiduen die geproduceerd worden door de boeren zonder vee een substantieel deel vormen van de voeropname van het vee gedurende het kritische droge seizoen (ongeveer 30%). Het verdwijnen van koolstof (C) door begrazing (0.3 tot 0.4 ton per jaar) van de velden van de boeren zonder vee had op de langere termijn tot gevolg dat de toch al lage opbrengsten nog verder afnamen. Het voorkomen van het begrazen van de gewasresiduen leidde tot een kleine toename van de bodemkwaliteit van de velden van de boeren zonder vee en tot een kleine toename van de gewasopbrengsten op de langere termijn, maar ook deze toename was niet genoeg om aan de voedsel vraag vanuit het huishouden te voldoen. Hoewel onze hypothese niet afgewezen hoefde te worden, waren de negatieve effecten relatief klein. Het toepassen van inputs in de gehele systeem (de gemeenschap) in de vorm van kunstmest samen met een verandering in het huidige beheer van de gewasresiduen en dierlijke mest door het herverdelen van de mest van de meer vruchtbare velden naar de arme velden, lijkt een veelbelovende strategie om de productiviteit van de gemeenschap als een geheel sterk te verhogen. De kans dat dit scenario ook echt geïmplementeerd wordt hangt af van de beschikbaarheid van kunstmest en de bereidheid van boeren om te investeren in het herstel van bodems om op de langere termijn de voordelen te kunnen behalen. Dit in tegenstelling tot de huidige strategie om alle organische materialen te concentreren op kleine oppervlaktes om daarmee eilanden van vruchtbare gronden te creëren waar gewasopbrengsten gewaarborgd zijn.

Er zijn voordelen in termen van productiviteit en efficiëntie door gewas en vee sterkerte integreren. Sommige voordelen kunnen worden behaald met relatief kleine technische aanpassingen en andere kunnen alleen worden behaald als de technische aanpassingen worden gecombineerd met radicale institutionele veranderingen en/of systeemverschuivingen.

# Resumen

Los suelos de los sistemas agrícolas minifundistas en África Sub-Sahariana son generalmente pobres en nutrientes. Los campesinos que manejan estos sistemas, dependen del uso de los recursos naturales para su subsistencia. Se sostiene que la integración de cultivos y ganado es una forma efectiva de reciclar nutrientes dentro de una explotación agrícola y entre varias explotaciones agrícolas. Sin embargo, hay mucha incertidumbre con respecto a cuales son los puntos críticos en la transferencia de nutrientes dentro de estos sistemas mixtos agrícola-ganadero. Cada paso en la transferencia de nutrientes representa un riesgo de ineficiencia; cuánto se pierde depende del tipo de sistema, su manejo, y de las condiciones del sitio. Los campesinos minifundistas en África reconocen el rol importante de los abonos orgánicos para mantener la fertilidad del suelo. Los campesinos con menos recursos podrían beneficiarse con la integración de ganado dentro de la explotación agrícola ya que éste sirve de seguro y ahorro lo cual ayuda a reducir el riesgo de la producción agrícola, además de los beneficios que ofrece el reciclado de la materia orgánica contenida en el estiércol para mantener la fertilidad del suelo. Ya que el ganado cumple diferente funciones dentro de la explotación agrícola, los campesinos manejan sus animales de acuerdo con la importancia que asignan a cada una de estas funciones. Al nivel de explotación agrícola, aumentos en la productividad de cada animal no necesariamente conducen a incrementos en la producción de los cultivos debido al reciclado del estiércol. Esta tesis es una contribución al desarrollo de una herramienta analítica, el marco de evaluación NUANCES (Nutrient Use in ANimal and Cropping systems – Efficiencies and Scales) diseñado para facilitar el análisis de controversias en sistemas mixtos minifundista, con énfasis en la identificación de oportunidades para la intensificación y maximización de los beneficios de la integración de cultivos y ganado. Para alcanzar este objetivo, se usaron como ejemplos distintos sistemas minifundistas mixtos de África de Este y del Sur y una combinación de métodos cualitativos (investigación participativa, tipología de explotaciones) y cuantitativos (experimentación y modelos).

En el Capítulo 2 se identificaron los pasos críticos donde la eficiencia en la transferencia de nutrientes (nitrógeno) en sistemas minifundistas mixtos puede incrementarse. Los sistemas fueron conceptualizados en cuatro subsistemas a través de los cuales hay transferencia de nitrógeno (N): 1. Ganado: los animales particionan el consumo en crecimiento, producción de leche, excreta y orina; 2. Recolección y manejo del abono orgánico: el tipo de estabulación y manejo de los animales determina la proporción de

excreta que puede ser recolectada para ser reciclada; 3. Almacenamiento/compostado del abono orgánico: el estiércol puede ser compostado puro o con el agregado de materiales vegetales; 4. Suelo y conversión por el cultivo: una parte de los nutrientes presente en los materiales agregados al suelo se vuelve disponible para ser absorbidos por el cultivo, y una parte de los nutrientes absorbidos es convertida en nutrientes que forman parte de las partes cosechables. Eficiencias parciales han sido calculadas y reportadas en la literatura con mayor frecuencia para el primer y último subsistema. La eficiencia de ciclado de N (Nutrient Cycling Efficiency, NCE) se calcula como el cociente entre producto por unidad de insumo. Las estimaciones de NCE para el subsistema ganado presentaron un rango entre 46−121%, 6−99% para el subsistema recolección, 30−87% para el subsistema almacenamiento/compostado de abono orgánico, y 3−76% para el subsistema suelo-cultivo. La eficiencia de reciclado de N del sistema es el producto de las eficiencias parciales. La aplicación directa de abonos verdes resulta en un uso más eficiente de los nutrientes contenidos en los materiales vegetales, con menores pérdidas que cuando son usados para alimentar animales. No obstante, el ganado no sólo es usado para producir estiércol sino que sirve otros propósitos dentro de la explotación agrícola. El estiércol puede contener cantidades relativamente grandes de nitrógeno que resultan en respuesta inmediata de los cultivos después de su aplicación. El uso eficiente del abono orgánico de origen animal depende críticamente de la eficiencia de recolección y compostado del estiércol, y de la sincronización entre mineralización y absorción por el cultivo. Medidas para mejorar la eficiencia de recolección y compostado son relativamente mas fáciles de diseñar e implementar que aquella destinadas a incrementar la recuperación de N por el cultivo.

El manejo eficiente del abono orgánico es crucial para mantener la producción de los cultivos de los campesinos minifundistas que generalmente usan pequeñas cantidades de fertilizantes minerales. El modelo HEAPSIM fue desarrollado para analizar NCE en explotaciones agrícola minifundistas de Kenia occidental (Capítulo 3). El modelo fue construido con datos de encuestas y observaciones de campo de excreta y manejo del abono orgánico animal, combinados con datos de experimentos y literatura para analizar pérdidas de masa y de nutrientes durante el compostado. Las simulaciones mostraron que el manejo del abono orgánico durante recolección y almacenamiento/compostado tiene un gran efecto en la eficiencia de retención de materia orgánica y nutrientes. Las diferencia en NCE entre explotaciones de diferente categoría se origina en las diferencias en la disponibilidad de recursos. Para los campesinos con menos recursos, las pérdidas de N que ocurren en todos los estadíos de reciclado son más grandes que para los campesinos con mayores recursos. Pérdidas del N contenido en la orina del ganado ocurre en todas las explotaciones, pero su impacto relativo es mayor para los campesinos de menos recursos, que reciclan cantidades menores de N al nivel de explotación. Con el manejo actual, el campesino mas pobre recupera menos de 1 kg N $y^{-1}$ en el compost de los 15 kg N excretados por el ganado. Mejoras en el almacenamiento del abono tienen poco efecto en incrementar la eficiencia de ciclado (NCE) del sistema del campesino más pobre, debido a las grandes pérdidas durante la fase de recolección del estiércol. Para los campesinos de más recursos, mejoras en el almacenamiento aumenta NCE y permite reciclar 30% del N excretado (ca. 30 kg N $año^{-1}$) por el ganado con pequeños cambios en infraestructura. Aumentar el numero de cabezas o mejorar la alimentación del ganado tendrían un mayor efecto en la disponibilidad de abono orgánico pero esto está limitado por la disponibilidad de forraje y la capacidad de inversión de los campesinos. Las cantidades absolutas de N reciclado (1−6, 4−17 y 7−18 kg N $año^{-1}$ para los campesinos de bajos, medios y más recursos, respectivamente) son pequeñas comparadas con las demandas de N del maíz (>50 kg N $ha^{-1}$), pero son significativas teniendo en cuenta el tamaño de las explotaciones (0.1–1.1 ha). Además de N, el abono orgánico animal proporciona otros nutrientes a los cultivos y ayuda a mantener la materia orgánica del suelo, ambos cruciales para garantizar el eficiente uso de los fertilizantes nitrogenados, lo que justifica la búsqueda de tecnologías para asistir a los campesinos a hacer un mejor uso de los abonos orgánicos. Protegiendo la pilas de abono orgánico animal o el compost con un film plástico reduce las pérdidas de masa y de N considerablemente. Para aumentar la NCE del sistema, se necesitan inversiones en la estabulación del ganado y reciclado de los nutrientes (básicamente N) contenidos en la orina.

La evaluación de la producción durante la vida productiva de las vacas permite diseñar intervenciones para mejorar la productividad de los sistemas lecheros minifundistas en las tierras altas de África del Este. Los planes de alimentación y tazas de mortalidad del ganado pueden tener efectos de largo plazo en la productividad y la rentabilidad de los sistemas lecheros (Capítulo 4). Experimentación con distintitas dietas durante lactaciones individuales no es suficiente para evaluar incrementos productivos debido a la escala temporal necesaria para el análisis de la producción durante la vida productiva de las vacas (más de 10 años para los sistemas lecheros de las tierras altas de África del Este). Por este motivo, un modelo dinámico fue usado para explorar el efecto de diferentes planes de alimentación durante la vida productiva de las vacas y para identificar estrategias que tendrían un impacto productivo. El modelo dinámico LIVSIM (Livestock Simulator), simula producción animal, la cual depende del potencial genético y de la alimentación del ganado. Se realizaron simulaciones de la producción de animales individuales durante su vida usando escenarios con diferentes dietas basadas en forrajes usados habitualmente en los sistemas analizados (pasto elefante (*Pennisetum purpureum*), rastrojo de maíz y alimentos concentrados), y se impusieron diferentes tazas de mortalidad para diferentes clases de edad. Las simulaciones mostraron que es posible ajustar la alimentación para maximizar la productividad durante la vida de la vacas suplementando alimentos concentrados para satisfacer los requerimientos nutritivos no sólo durante la lactancia, sino también durante desarrollo inicial para poder reducir la edad a primera concepción y así extender la vida productiva. La productividad de las vacas durante toda su vida aumentó cuando se evitó la desnutrición durante el período seco suplementando con 0.5 kg por día de alimentos concentrados, práctica que no es común en los sistemas minifundistas lecheros. Análisis de supervivencia (Survival análisis) indicaron que los períodos entre pariciones se alargan significativamente cuando las vacas no reciben alimentos concentrados. Las simulaciones en las que se impuso mortalidad al azar mostraron una reducción de la vida productiva, el número de terneros y una reducción de alrededor de 43−65% de todos los indicadores de productividad. No tiene mucho sentido elegir las mejores dietas cuando las tazas de mortalidad del ganado joven son tan altas como 15% por año. Para aumentar la productividad de los sistemas lecheros minifundistas, se deben diseñar programas de salud para reducir las tazas de mortalidad conjuntamente con medidas que estén destinadas a aumentar la productividad de las vacas durante toda su vida y no solamente los rendimientos de leche diarios.

La diversidad en las actividades agrícolas en una explotación pueden aumentar la estabilidad de su producción y reducir el riesgo asociado a la producción agrícola para campesinos minifundistas. La integración de las actividades agrícolas usando los productos de una actividad como insumos para otra actividad, pueden reducir la dependencia en insumos externos. En la práctica, diversidad e integración en sistemas agrícolas no están claramente definidas, lo cual dificulta la exploración de sus beneficios potenciales. En el Capítulo 5, se introduce un método basado en ‘network análisis (NA)’ para caracterizar y evaluar diversidad e integración de sistemas agrícolas. El indice de reciclado de Finn se usaron para caracterizar el grado de integración de las actividades agrícolas. La diversidad se caracterizó usando medidas de teoría de la comunicación: ‘average mutual information’ (AMI) y su limite superior ‘statistical uncertainty’ ($H_R$). El método se aplicó a un sistema mixto de las tierras altas del norte de Etiopia. En el ejemplo se usó flujos de N para ilustrar la utilidad del método. Los indicadores parecen útiles para sustentar las discusiones sobre la sustentabilidad de sistemas agrícolas diversos y permiten evaluar los efectos de diferentes prácticas de manejo para mejorar el diseño de los sistemas agrícolas. La definición del sistema agrícola y sus compartimentos (actividades agrícolas) y la escala usada para el análisis, tiene un gran efecto en los resultados obtenidos. El potencial de NA para elaborar recomendaciones sobre manejo sustentable depende de definiciones apropiadas de sistema y de los objetivos del estudio.

Ya que los campesinos minifundistas en África sub-Sahariana dependen del uso de los recursos naturales para su subsistencia, se debe aumentar el uso de nutrientes para poder compensar la exportación de nutrientes debido a la venta de cosechas y las pérdidas de nutrientes debido a las prácticas agrícolas. Aumentando la integración a través de reciclado interno puede aumentar la eficiencia en el uso de nutrientes. En el Capítulo 6 se investigó las características de los flujos y el reciclado de N para explorar hasta que punto las propiedades de la redes de reciclado de nutrientes se relacionan a la capacidad de los sistemas agrícolas para sustentar a las familias campesinas. Los estudios de caso incluyeron explotaciones agrícolas minifundistas de diferente estrato social en tres sitios diferentes en Tigray en el norte de Etiopia, en Kakamega en el oeste de Kenia y en Murewa en el noreste de Zimbabwe. Estas explotaciones fueron concebidas como redes en las cuales la familia y las diferentes actividades agrícolas representan diferentes compartimentos y los flujos de N representan las conexiones entre éstos. Se usaron indicadores para evaluar el tamaño, la actividad, el reciclado y la organización de la red de flujos de N. Estos indicadores se compararon con su producción de biomasa y de autosuficiencia alimentaria. Los sistemas agrícolas de Tigray utilizaron alrededor de 1.5 y 3 veces más N que los sistemas en Murewa y Kakamega, respectivamente. Las cantidades de N reciclado fueron relativamente pequeñas para todos los sistemas (menos de 2.5 kg N per capita por año). La dependencia en insumos externos para sustentar la producción actual fue más grande para los campesinos de más escasos recursos que para los demás, que tenían mayores stocks de N per capita en sus suelos. Los campesinos más pobres no alcanzaron autosuficiencia alimentaria en ninguno de los tres sitios. Las medidas de realización del sistema agrícola estuvieron positivamente relacionadas al tamaño de la red de flujos de N, a la organización de la red y al reciclado, pero las eficiencias de utilización difirieron a través de los sitios en relación con el tamaño de los stock en el suelo y la importancia del ganado para los flujos de N del sistema. El análisis de redes (NA) parece promisorio para evaluar las propiedades de sistemas agrícolas estudiando dependencia en insumo biofísicos del ambiente externo a la explotación y la organización interna de la explotación. Ya que aumentos en el tamaño y en la organización de la red de flujos de N condujeron a aumentos en productividad y en autosuficiencia alimentaria, la combinación de ambas estrategias beneficiaría no solo productividad

sino también adaptabilidad y fiabilidad de los sistemas mixtos minifundistas.
El agregado de materia orgánica es necesario para aumentar la productividad de los suelos inherentemente pobres de los sistemas agrícolas comunales y mixtos del noreste de Zimbabwe. En estos sistemas, el ganado se alimenta de pasturas que se manejan colectivamente, con el hato del pueblo pastando en pasturas naturales durante la estación húmeda y en residuos de cultivo durante la estación seca. Esto crea diferentes tipos de interacciones entre los miembros de la comunidad: los campesinos con y sin ganado, incluyendo competencia por los recursos orgánicos. En el Capítulo 7 se exploraron la magnitud de las interacciones en términos de flujos de nutrientes y los efectos de largo plazo de las prácticas actuales en la productividad del suelo. La hipótesis fue que el manejo colectivo de los forrajes trae consecuencias negativas para los campesinos sin ganado. Se usó información de prácticas de cultivo y de manejo del ganado que fue recogida en un pueblo del área comunal de Murewa en el noreste de Zimbabwe, y un modelo dinámico de explotación agrícola (NUANCES-FARMSIM). Los submodelos de FARMSIM fueron calibrados y testeados con información existente para la misma área, y fue adaptado para incluir las principales interacciones al nivel del comunidad. Las simulaciones de 10 años mostraron que las pasturas comunales contribuyeron a la mayoría del consumo anual del ganado (aproximadamente 75%), y que los residuos de cultivo producidos por los campesinos sin ganado representaron una cantidad sustancial (aproximadamente 30%) del consumo durante la estación seca. La remoción de carbono (C) ( 0.3–0.4 t C $y^{-1}$) de éstos campos resultó en el largo plazo en una reducción de los rendimientos de granos. Impidiendo el acceso del ganado a los campos de los campesinos sin ganado aumentó la calidad de sus suelos y los rendimientos modestamente, pero no lo suficiente como para satisfacer las necesidades alimentarias de estas familias. Aunque la hipótesis de trabajo no fue rechazada, los efectos negativos fueron relativamente pequeños. Agregando insumos a toda la comunidad en la forma de fertilizantes minerales conjuntamente con cambios a las prácticas actuales de los residuos de cosecha y los abonos de origen animal (redistribuyéndolos de los campos mas fértiles a los más pobres) parece ser una estrategia promisoria para aumentar la producción de los campos de toda la comunidad. Que esto ocurra depende de la disponibilidad de fertilizantes y de la decisión de los campesinos de invertir en rehabilitar sus suelos para obtener beneficios de largo plazo envés de concentrar todos sus recursos en áreas pequeñas creando islas de fertilidad donde los rendimientos se aseguran.
Se puede obtener beneficios en términos de productividad y eficiencia en el uso de recursos al integrar más cercanamente cultivos y ganados en sistemas mixtos minifundistas. Algunos de esos beneficios se pueden obtener con simples cambios técnicos y otros necesitan de cambios radicales institucionales y de los sistemas agrícolas.

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Mariana

Wageningen, 2 de Setiembre de 2008

# List of Publications

**1. Articles recently submitted to peer-reviewed journals**

Rufino, M.C., J. Dury, P. Tittonell, M.T. Van Wijk, S. Zingore, M. Herrero and K.E. Giller. 2008. Collective management of feed resources at village scale and the productivity of different farm types in a smallholder community of North East Zimbabwe. Submitted to Agric. Syst.

Rufino, M.C., P. Tittonell, P. Reidsma, S. López-Ridaura, H. Hengsdijk, K.E. Giller and A. Verhagen. 2008. Characterisation of N flows and cycling in smallholder crop-livestock systems of the highlands of East and southern Africa through network analysis. Submitted to Nutr. Cycl. Agroecosyst.

Rufino, M.C., H. Hengsdijk and A.Verhagen. 2008. Network analysis to assess the integration of diversified farming systems. Submitted to Nutr. Cycl. Agroecosyst.

Van Wijk, M.T., P. Tittonell, M.C. Rufino, M. Herrero, C. Pacini, N. De Ridder and K.E. Giller. 2008. Identifying key entry-points for strategic management of smallholder farming systems in sub-Saharan Africa using the dynamic farm-scale simulation model NUANCES-FARMSIM. Submitted to Agric. Syst.

Tittonell, P., M.T. Van Wijk, M. Herrero, M.C. Rufino, N. De Ridder and K.E. Giller, 2008. Inefficiencies and resource constraints -exploring the physical feasibility of options for the intensification of smallholder crop-livestock systems in Vihiga district, Kenya. Submitted to Agric. Syst.

**2. Articles published and accepted for publication in peer-reviewed journals**

Rufino, M.C., M. Herrero, M.T. Van Wijk, L. Hemerik, N. de Ridder and K.E. Giller. 2008. Lifetime productivity of dairy cows in smallholder mixed systems of the highlands of East Africa. Animal, under revision.

Rufino, M.C., A. Verhagen, H. Hengsdijk, J.W.A. Langeveld, R. Ruben, J. Dixon and K.E. Giller. 2008. Low-cost analytical approach for economic and environmental performance assessment of farm households systems: Application to mixed crop-livestock systems in the Ethiopian highlands. J. Sust. Agric., In press.

Rufino, M.C., P. Tittonell, M.T. Van Wijk, A. Castellanos-Navarrete, R.J. Delve, N. de Ridder and K.E. Giller. 2007. Manure as a key resource within smallholder farming systems: analysing farm-scale nutrient cycling efficiencies with the NUANCES framework. Livest. Sci. 112: 273-287.

P. Tittonell, M.T. Van Wijk, M.C. Rufino, J.A. Vrugt and K.E. Giller. 2007. Analysing trade-offs in resource and labour allocation by smallholder farmers using inverse modelling techniques: A case-study from Kakamega district, western Kenya. Agric. Syst. 95: 76-95.

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**3. Books and book sections**

Bagamba, F., R. Ruerd and M.C. Rufino. 2007. Determinants of Banana Productivity and Technical Efficiency in Uganda. in: (Eds) M. Smale and W.K. Tushemereirwe, "An Economic Assessment of Banana Genetic Improvement and Innovation in the Lake Victoria Region of Uganda and Tanzania". IFPRI Research Report 155. http://dx.doi.org/10.2499/9780896291645RR155.

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**4. Abstracts and Proceedings**

Rufino, M.C., P. Reidsma, S. López-Ridaura and P.Tittonell, 2008, Network analysis to asses the productivity and resilience of complex agro-ecosystems. Food Security and Environmental Change, 2-4 April 2008, Oxford, UK. Book of Abstracts.

Rufino, M.C., H. Hengsdijk and A. Verhagen. 2007. A methodology to assess diversification and integration of farming systems. Farming Systems Design conference, Catania, Italy, 10-12 September 2007. Book of Abstracts.

Van Wijk, M.T., M.C. Rufino, P. Tittonell, C. Pacini, N. de Ridder and K.E. Giller. 2007. Possible entry points for improved management of smallholder farming systems in sub-Saharan Africa. Farming Systems Design conference, Catania, Italy, 10-12 September 2007. Book of Abstracts.

Rufino, M.C., M.T. Van Wijk, A. Verhagen and K.E. Giller. 2006. Assessing opportunities for interventions to increase C sequestration in Sub-Saharan African smallholder farming system within the 4th WSEAS International Conference on environment, ecosystems and development. Venice, Italy, 20-22 November 2006.

Rufino, M.C., M. Herrero, M. Van Wijk, N. de Ridder and K.E. Giller. 2006. Factors affecting the lifetime productivity of dairy cows in smallholder crop-livestock systems of Central Kenya. Tropentag: Prosperity and Poverty in a globalized world: Challenges for Agricultural Research, Bonn, Germany, 11-13 October, 2006. Book of Abstracts.

Van Wijk, M.T. P. Tittonell, M.C. Rufino, M. Herrero and K.E. Giller. 2006. Dynamics of Resource and Labour Allocation in Smallholder Farms of the Western Kenya Highlands. Tropentag: Prosperity and Poverty in a globalized world: Challenges for Agricultural Research, Bonn, Germany, 11-13 October, 2006. Book of Abstracts.

Giller, K.E., N. de Ridder, M.C. Rufino, P. Tittonell, M.T. Van Wijk and S. Zingore. 2006. Manure as a key resource to sustainability of smallholder farming systems in Africa: An introduction to the NUANCES framework. Ramiran 12th International Conference, Denmark, 11-13 September 2006, Book of Abstracts.

Langeveld, J.W.A., A. Verhagen, H. Hengsdijk, M.C. Rufino, R. Ruben, K.E. Giller, and D. Jansen. 2005. Application of economic and ecological indicators in farm household and regional analysis: introducing some approaches and insights. International Symposium Territoires et enjeux du développement régional. Lyon, France, 9-11 March 2005.

Bagamba, F., R. Ruben, A. Kuyvenhoven, R. Kalyebara, M.C. Rufino, E. Kikulwe and W.K. Tushemereirwe. 2004. Determinants of resource allocation in low input agriculture: The case of banana production in Uganda. Proc. Am. Agric. Econ. Assoc. Annual Meeting, Denver, USA, 1-4, August 2004.

Rufino, M.C., E.R. Romero, J. Scandaliaris, F.D. Pérez Zamora and A. Bulacio. 2001. Agronomical, industrial and economic impacts of sugarcane chemical ripening. Proc. 24th Int. Soc. Sugarcane Technol. Congress, Australia II: 161-163.

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Pérez Zamora, F.D., J. Scandaliaris, E.R. Romero and M.C. Rufino. 2001. Diagnosis parameters for improving N fertilisation in sugarcane. Proc. 24th Int. Soc. Sugarcane Technol. Congress, Australia II: 164-167.

Pérez Zamora, F.D., M.C. Rufino, J. Scandaliaris and E.R. Romero. 2000. Use of Principal Component Analysis in the study of factors associated with sugarcane response to N fertilizer under subtropical conditions of Tucumán-Argentina. Int. Soc. Sugarcane Technol. Agronomy workshop, Miami, FL, USA. Book of abstracts.

### 5. Publications in Spanish

17 Artículos de investigación y difusión y 8 trabajos presentados en conferencias y talleres.

# PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

**Review of Literature (5.6 ECTS)**
- Nitrogen cycling efficiencies through resource-poor African crop-livestock systems: a review (2004)

**Writing of Project Proposal (7 ECTS)**
- Analysing diversity within crop-livestock systems and opportunities for improving smallholders' livelihoods (2005)

**Laboratory Training and Working Visits (5.6 ECTS)**
- Field visit AfricaNUANCES project in Kenya; ILRI-Nairobi (2005)
- Field visit AfricaNUANCES project in Tanzania; LZARDI (2006)
- Field visit AfricaNUANCES project in Zimbabwe; University of Zimbabwe (2007)
- Field visit AfricaNUANCES project in Mali; IER Sikasso (2007)

**Post-Graduate Courses (6 ECTS)**
- Multiple Criteria Decision Making in Agriculture Theory and Applications; Mansholt Graduate School (2005)
- Multi-Agents Systems for Natural Resources Management; Mansholt Graduate School (2006)
- Survival Analysis (2007)

**Deficiency, Refresh, Brush-up Courses (4.2 ECTS)**
- Elementary programming; IT group, WUR (2005)

**Competence Strengthening / Skills Courses (0.3 ECTS)**
- Career assessment (2008)

**Discussion Groups / Local Seminars and Other Scientific Meetings (9 ECTS)**
- Statistics, maths and modelling in Production Ecology and Resource Conservation (2005/2006/2007)
- Annual AfricaNUANCES workshops in Wageningen, Arusha / Tanzania (2005/2006/2007)
- Working visits to ILRI-Nairobi, Kenya (2005/2006/2007)

**PE&RC Annual Meetings, Seminars and the PE&RC Weekend (1.5 ECTS)**

- PE&RC Weekend (2005)
- WIAS Seminar: Modelling ecosystems and farmers' decision making with fuzzy logic (2007)
- PE&RC Seminar: Farming futures in Sub-Saharan Africa (2008)

**International Symposia, Workshops and Conferences (6 ECTS)**

- Farming Systems Conference with presentation: A methodology to assess diversification and integration of farming systems; Catania, Italy (2007)
- Lack of resilience in African smallholder farming: exploring measures to enhance the adaptive capacity of local communities to pressures climate change with presentation: Unravelling complexity in crop-mixed smallholder farming systems: challenges for modelling; Harare, Zimbabwe (2007)
- Food Security and Environmental change with presentation: Network analysis to asses the productivity and resilience of complex agro-ecosystems; Oxford, UK (2008)

**Supervision of MSc Students**

- Suijkerbuijk, N: Livelihood strategies; the case of diversification and risk attitudes of smallholders in Central Kenya (2006)
- Houssain, L: Testing of spectral indices as estimators of grassland biomass in Bukoba, Tanzania (2006)
- Byjesh Kattarkandi: Farmer's Carbon: exploring the soil carbon sequestration potential in Bukoba district, North west Tanzania (2007)
- Castellanos-Navarete, A: Cattle feeding strategies and manure management in smallholder farms of western Kenya (2007)
- Dury, J: Spatio-temporal analysis of feed resource availability and nutrient transfers through animal management: a case study of smallholder farming system in Murewa, Zimbabwe (2007)
- Vetois, Y: Fodder legumes to lift feed deficit of dairy cows during the hot dry season: a feeding trial under farming conditions in Koutiala, Mali (2007)

# Curriculum Vitae

Mariana Cristina Rufino was born in the subtropical North West of Argentina on 28 March 1972. Her secondary school education took place at the Fine Arts School of the University of Tucumán, where she obtained a diploma for teaching fine arts in primary schools in 1989. From 1990 to 1996, she studied Agronomy at the same University of Tucumán, where she graduated as Agronomic Engineer with distinction. She worked for a short period as technical adviser in vegetable production in the private sector, and in 1997 joined the Sugarcane Agronomy department of the Obispo Colombres Experimental Station in Tucumán, Argentina. From 1997 to 2001, Mariana worked on ecophysiology of sugarcane developing and testing technologies for improving the productivity of the commercial sugarcane production in the province of Tucumán, in close cooperation with farmers. She tested chemical ripening of sugarcane and other technologies for increasing the efficiency of sugar recovery through crop husbandry. In that period, Mariana published technical papers, extension bulletins and participated in several scientific meetings. In 2000, she started postgraduate studies at the University of Buenos Aires leading to a Master degree in Crop Sciences, and continued these studies at Wageningen University in the MSc programme in Crop Sciences. She studied biophysical constraints to the productivity of cooking bananas in central and southern Uganda, and wrote a short thesis on N cycling in crop-livestock African systems, and graduated in February 2004. Soon after graduation, she started working at the Agrosystems Business Unit of Plant Research International at Wageningen, where she participated in a research commissioned by FAO to develop a methodology to assess the benefits of diversification and integration in farming systems. In February 2005, Mariana joined the Plant Production System Group of Wageningen University to work in the development of the analytical framework of the AfricaNUANCES project, and wrote this PhD thesis during that period. Presently Mariana continues working at the Plant Production Systems Group investigating the applicability of the NUANCES tools to assess the impact of climate change on African farming.