# MODELING LIVESTOCK-FORAGE SYSTEMS WITH NITROGEN CYCLING IN THE SMALLHOLDER DAIRYING

By

Francis Tibayungwa

B.Sc. Agric. (Mak), M.Sc. Agric. (Syd)

A THESIS SUBMITTED TO THE SCHOOL OF
GRADUATE STUDIES FOR THE AWARD OF THE DEGREE OF
DOCTOR OF PHILOSOPHY (AGRICULTURE)
OF MAKERERE UNIVERSITY
KAMPALA, UGANDA
JULY 2010

## DECLARATION

This is a result of my efforts and to the best of my knowledge, no part of it has been submitted for any award in any College or University

Signature: ______________________________ Date: ________________

Francis Tibayungwa

## APPROVAL BY SUPERVISORS

This thesis has been under our supervision and has our approval for submission

Signature: ______________________________ Date: ________________

Professor J. Y. T. Mugisha (Ph.D)

Signature: ______________________________ Date: ________________

M. Nabasirye (Ph.D)

*To My Parents*

# Table of Contents

# List of Tables

# List of Figures

# Acronyms

| | |
|---|---|
| AFRC | Agricultural and Food Research Council |
| AGDP | Annual Gross Domestic Product |
| FAO | Food and Agricultural Organisation of the United Nations |
| HPI | Heifer Project International |
| MAAIF | Ministry of Agriculture Animal Industry and Fisheries |
| MLD | Ministry of Livestock Development |
| NGO | Non-governmental organization |
| NRC | National Research Council |
| OSSREA | Organization for Social Science Research in Eastern and Southern Africa |
| PMA | Plan for Modernization of Agriculture |
| SCA | Standing Subcommittee on Agriculture |
| UBOS | Uganda Bureau of Statisics |

# Acknowledgements

I would like to thank my supervisors, Prof. J. Y. T. Mugisha and Dr. M. Nabasirye for their many suggestions and constant support during this research.

My sincere appreciation to my wife for the support, patience, love and understanding.

I wish to thank the farmers and research assistants for their time and cooperation, and any other person (or persons) that may have contributed directly or indirectly to the completion of the research.

Finally, I wish to thank the following: i@mak for the financial support; Staff at the School of Graduate Studies; Staff at the Department of Human Resource; Staff at the Department of Animal Science, Makerere University.

# Abstract


In this research, systems dynamics and the dynamical systems approaches are used to study livestock-forage systems. For the systems dynamics the model for growth of dairy heifers fed on napier grass with and without legume supplementation, and nitrogen excretion and recycling is developed. For the dynamical systems approach, differential equations are formulated and nondimensionalised to reduce the number of parameters and simplify the analysis. The differential equations represent forage growth, animal intake, stocking density, and liveweight gain for the one and two dimensional systems whereas the three dimensional system incorporates nutrient excretion and recycling.

It is established in this study that when Elephant grass is the sole feed, increased crude protein (CP) intake leads to higher weight gain, and that metabolisable energy (ME) is limiting if forage CP exceeds 110 g/kgDM. At napier CP $\leq$ 75 g/kgDM supplementation even up to 40% yields less DG compared to unsupplemented napier at CP $\geq$ 100 g/kgDM. With application of excreted N to napier grass growth, the stocking level can be increased by 66.7%.

For one dimensional dynamical system, the model results show that at maximal forage utilisation there is discontinuous stability. For a two dimensional model, with increase in $\beta$ (a measure of relative forage intake), the system evolves into a stable limit cycle. For the three dimensional model with $\alpha$, a measure of soil nutrient replenishment, as a bifurcation parameter, the system exhibits a stable fixed point, a stable limit cycle, an unstable limit cycle, hysteresis, and local stability.

The study offers comprehensive understanding of the dynamics and sustainability of livestock-forage system and nitrogen recycling, and can be used to predict possible outcomes of different management strategies.

CHAPTER 1

# Introduction

## 1.1 Background to the study

With poverty alleviation and food security as the primary goals in the developing world (Pell, 1999), not only must the current problems of food availability and distribution be addressed, but future demands due to population growth also must be anticipated as the population in sub-Saharan Africa will probably more than double by 2020 (Werblow, 1997). Although global food production per capita increased 15% from 1978 to 1998 on top of a world population increase of 45% (Barrett, 1999), in 1997 agricultural productivity in sub-Saharan Africa decreased by 1% (FAO, 1998). Therefore food production in sub-Saharan Africa has not been commensurate with demand.

Among the biophysical factors that reduce agricultural productivity, declining soil fertility often is seen as a primary culprit in sub-Saharan Africa (Sanchez et al., 1997). Scherr (1999) estimated that 65% of the agricultural land and 31% of the permanent pasture in Africa are degraded due to nutrient mining associated with crop production (Sherpherd et al., 1995). Therefore attention to management of soil soil nutrient pools is critical to restoring and maintaining soil productivity (Fernandes and Sanchez, 1990).

Livestock are integral to most African farming systems and can make an important contribution to the restoration and maintenance of soil fertility (Powell et al., 1996). By harvesting and relocating nutrients, animals play a significant role in improving soil fertility and crop yields. However the nutrient flux is not sufficient to offset nutrient deficits acceptable for crop growth (Murwira et al., 1995; Powell and Valentin, 1998). However the nutrient exchange between animals and plants represents a major impact point in nutrient management decisions for sustainable agricultural productivity (Stuth et al., 1995).

Given the high population densities, in a number of areas in East Africa, there is demand for effective integration of crops and livestock for prudent land use and efficient nutrient recycling in Africa (Thorne and Tanner, 2002; Elbasha et al., 1999; Harris, 1995; Powell et al., 1996; Powell and Valentin, 1998; Agbenin and Goladi, 1998).

Livestock excreta make an important contribution to soil nutrient inputs and in many developing countries are the only significant inputs (Sheldrick et al., 2003). A case study (Esilaba et al., 2002), showed a net negative nutrient balance of $-59$ kg N in a sole crop production system; against a net positive balance of 1 kg N in a livestock system. Therefore, the inevitable decline in crop yields per hectare can be mitigated by systematic integration of livestock to provide manure for cropland (Schlecht et al., 2004).

Livestock production is becoming increasingly intensive to cope for the nutritional needs of an increasing human population and declining per capita land landholding (de Wit, 1992). In Uganda several factors are responsible for increasing land pressure (OSSREA, 1999); as well as urban developments.

Higher production levels are possible on farms through the use of external input, notably, commercial fertilizer and feeds, which a number of resource constrained farmers cannot afford. Intensification in the smallholder dairy cattle industry has adopted stall-feeding (also known as "cut-and-carry") where one to three animals are fed indoors instead of *in-situ* grazing. In addition to nutrients lost through products, such systems are susceptible to localized harvests from fodder plots and dumping around cow sheds. The estimates of average net losses of nutrients in sub-Saharan Africa can be as high as 49 kg/ha per year (Stangel, 1995); this figure is four times as high as the average use of fertilizer, with Uganda among the countries with the highest levels of nutrient depletion (Woelcke et al., 2002). The voluminous amounts of excreta generated requires effective ways of handling to avoid pollution especially in urban and peri-urban areas; and to reduce nutrient losses from volatilization (Nennich et al., 2006).

Because of the many components and complexity of their interaction in a livestock-forage system, there is need to use simulation models to provide farmers and advisory service providers with integrative decision support tools (Rickert et al., 2000). This approach reduces time and costs of demonstrating results (Pandey and Hardaker, 1995); and provides valuable insights for policy formulation and technology design. The approach was used to acquire comprehensive understanding of the dynamics of nutrient cycling in livestock-forage production systems in Uganda.

## 1.2 Statement of the problem

The study is designed to respond to a hierarchy of challenges. The increasing demand for food including livestock products requires commensurate increase in production. The declining resource base including land and the incumbent nutrient pools needs prescriptions that enhance nutrient use efficiency in the dairy production systems. Competing demands for land between crops and livestock underscores the importance of crop-livestock integration to offset unacceptable imbalances between the crop and livestock sub-sectors of the agricultural economies. Management of nutrient dynamics between crops and livestock components of the production systems is the generic problem to be addressed in the study. The core problem is limited capacity to make timely decisions on technology and/or policies to offset impending threats of nutrient depletion and declining productivity in smallholder dairy systems. The development of this capacity needs a comprehensive understanding of components and their interactions in the dairy system; and integrative decision support tools to generate putative options for testing against real-time situations.

## 1.3 Objectives of the study

The overall objective of the study was to develop simulation models for evaluating sustainability of nutrient dynamics and growth of replacement heifers in smallholder dairy systems.

The specific objectives were:

1. To describe current management and use of animal excreta in stall-feeding dairy cattle system.

2. To determine the effect of forage legumes supplementation on nutrient balance and growth of dairy replacement heifers

3. To determine the effects of levels of N intakes, digestibility and rumen degradability on proportions of N excretions in feaces and urine.

4. To determine the potential value of excreted N for forage and animal production.

5. To evaluate sustainability of livestock-forage systems where livestock manure is the only source of nitrogen input for forage production.

## 1.4 Justification of the study

In stall-fed dairy cattle system, excreted nutrients in manure, such as nitrogen would be a source of fertilizer for forage growth. However, excreted nitrogen depends on interaction between animal and feed characteristics, digestibility and route of excretion. Therefore modeling the nutrient flows in the livestock-forage systems will contribute to comprehensive understanding of the nutrient flow dynamics in livestock-forage system that is crucial for decision making and appropriate management strategies.

## 1.5 Thesis outline

This thesis is organised along the objectives of the study. Chapter 1 is a general overview of constraints in smallholder dairying in urban and peri-urban areas in Uganda and the relevance of livestock manure in nutrient cycling.

Chapter 2 is a general review of literature on feed resources, nitrogen metabolism, nutrient cycling, and use of simulation modelling in smallholder livestock-forage systems.

Chapter 3 gives a description of the production characteristics and use of animal excreta in livestock-forage system in urban and peri-urban areas of Mbarara district.

In Chapter 4, the development and use of a simulation model to predict heifer growth up to mating weight is given.

Chapter 5 is an extension of the model developed in Chapter 4 to incorporate forage legumes supplementation to basal diet of elephant grass.

In Chapter 6 excreted nitrogen in manure and urine is predicted based on nutrient intake, digestibility and degradability of feedstuffs. Then a simulation model developed in Chapter 4 is extended to interface the excreted N with a forage growth subcomponent.

Chapter 7 describes the long-term livestock-forage system dynamics (with and without nutrient cycling) using a dynamical systems approach.

In Chapter 8 the findings of the study are discussed, conclusions and recommendations are made with respect to practical implications for the stall-feeding dairy system.

CHAPTER 2

# Literature Review

## 2.1 Livestock-crop systems

According to Delgado et al. (1999), by the year 2020 the world demand for foods of animal origins is expected to increase with virtually all the increased demand coming from the developing countries. But increasing pressure on grazing land strongly suggests that smallholder resource poor farmers who produce 50% of the meat and 90% of the milk are to benefit from increased market opportunities (Von Kaufmann, 1999; Thornton and Herrero, 2001). However as a coping mechanism to climate change and variability, farmers in Africa are anticipated to shift from crop to livestock production (Jones and Thornton, 2009).

## 2.2 Models in livestock-forage systems

Models capable of predicting animal performance from given plant and animal characteristics have been developed (Illius and Allen, 1994; Herrero et al., 1998). They range from relatively simple requirements systems such as those proposed by SCA (1990), AFRC (1993) and NRC (1996) to models that represent the flow of feed through the gastrointestinal tract of ruminants (Baldwin et al., 1987; Illius and Gordon, 1991; Sniffen et al., 1992; Kebreab et al., 2002). However, these models are valuable for livestock that are fed both forage and concentrates. Models reflective of the smallholder feeding regimes are necessary to predict nutrient flows through these systems.

## 2.3 Modeling livestock and nutrient cycling

Whereas on a typical dairy farm in the developed countries nitrogen fertilizers are the major nitrogen input (Rotz et al., 1999; Brown et al., 2005), in the developing countries livestock excreta are the only significant nitrogen input (Sheldrick et al., 2003). Animal manure can be a valuable source of nitrogen for crop growth (Rotz et al., 1999), but the overall efficiency of conversion of nitrogen inputs into products is determined by the efficiency of nitrogen cycling through the soil-plant-animal within the production system (Ledgard, 2001). Therefore efficient nutrient management requires integration of the interrelated aspects of manure management, soil conservation, crop production, animal nutrition, and the economics (Wang et al., 2000).

Several modeling efforts have developed simulations for livestock production systems. These include the model developed by Kohn et al. (1997) of nitrogen management on a dairy production enterprise, the model by Dou et al. (1996) to predict the consequences of management practices, the model by Rotz et al. (2005) for simulating feed intake, animal performance and manure excretion, and the regression equations by Nennich et al. (2005) to predict manure and nutrient excretion from dairy cattle. However, these models are based on the production systems that are not representative of the developing world where the factors affecting the quality of livestock excreta are scarce, scattered and not adequately packaged into useful information.

The role of livestock in nutrient cycling at household level has been reported by Pilbeam et al. (2000) in research aimed at estimating nutrient balances. However, according to Thorne and Tanner (2002), research by Pilbeam et al. (2000) grievously under-researched the role of livestock in whole-farm nutrient dynamics by including only the most basic and static livestock; and ignored the biological mechanisms that enable livestock to contribute to the sustainability of smallholder agriculture. Among the gaps are models that address the most dominant, napier based dairy systems in the East and Central African region.

## 2.4 Napier grass (*Pennisetum purpureum*) as the major feed resource in smallholder dairying

Several studies on dry matter yield, nutritive value, chemical composition, digestibility and animal performance have been conducted (Kabirizi, 2006; Kabi et al., 2005; Nyambati et al., 2003; Muia et al., 2000a; Kariuki et al., 1998; Ruiz et al., 1992; Sollenberger and Jones, 1989; Anindo and Potter, 1986; Ogwang and Mugerwa, 1976).

### Dry matter yield

In Uganda, Napier grass yields of 22.5 tons $ha^{-1}$ were reported by Kabi and Bareeba (2007). In Kenya, on-farm DM yield from ranged from 1 to 6 tons $ha^{-1}$ per year (Wouters, 1987) with little or no fertilizer. Comparable napier grass DM yields have been recorded elsewhere in the tropics (Woodard and Prine, 1991; Ferraris and Sinclair, 1980). However, with high rates of fertilizer application, DM yields of up to 85 tons DM $ha^{-1}$ have been reported (Skerman and Riveros, 1990). Dry matter (DM) yield of napier grass surpasses that of other tropical grasses (Humphreys, 1994; Skerman and Riveros, 1990).

### Nutritive value

According to Norton and Poppi (1995), nutritive value is the amount of feed ingested and the efficiency with which nutrients are extracted from a given feed . Compared to other tropical pasture grasses such as *Digitaria decumbens*, *Chloris gayana*, *Pennisetum clandestinum* and *Panicum maximum*, relatively few data exist on the effects of feeding napier grass on animal performance (Minson, 1990). But is known that vigorous growth habit and poor persistence under grazing makes napier grass ideal for stall-feeding system.

Forage intake is influenced by digestible DM and CP content and the extent of degradation (Minson, 1990). Therefore, the ultimate measure of nutritive value would be animal performance. Given that animal performance is closely associated with the capacity of a feed to supply nutrients required for different productive states (Sniffen et al., 1992), weight gain is a function of intake, forage composition and digestibility.

## Chemical composition and digestibility

The increase in age in grasses is usually negatively associated with CP content (Kabirizi, 2006; Woodard and Prine, 1991; Minson, 1990; Skerman and Riveros, 1990; Ogwang and Mugerwa, 1976). This is due to the decline in leaf:stem ratio causing a change in the chemical composition resulting in reduced feeding value (Minson, 1990). Thus quality could affect voluntary feed intake and animal performance in terms of body weight gain.

The cell wall component is the most important factor affecting forage utilization (Van Soest, 1994). It comprises the major fraction of forage DM and its extent of degradation by the microflora has important implications on forage digestibility and intake (Paterson et al., 1994). The cell wall content in napier grass increase less prominently with age compared with other tropical grasses (Minson and McLeod, 1970) and thus less decline of DM digestibility per day (Minson, 1990; Reid et al., 1973). This makes napier grass a more attractive feed compared to other grasses in the tropics.

## Animal Performance

Little information is available on animal performance especially on the growth of dairy heifers. MLD (1991) recommends weaning weight for dairy heifers of 70 kg body weight and a target 300 kg, to be attained by 18 months of age for first service in the smallholder dairy farming system. This recommendation can be met if heifers gain at least 0.5 kg day$^{-1}$ but on average, less than 0.25 kg is observed in the smallholder system (Gitau et al., 1994), and therefore puberty is not achieved until after 24 months. This is mainly due to the low quality of napier grass fed on the farms and the lack of concentrate feeding (Wouters, 1987).

Weight gain of dairy heifers vary widely depending on napier grass quality, the level and type of supplement used. Weight gains of cattle on tropical pastures without supplementation can be as high as 0.7 kg day$^{-1}$ (Humphreys, 1994), but they mostly range between 0.4 and 0.5 kg day$^{-1}$ (Stobbs and Thompson, 1975). For heifers weighing 181 kg liveweight, fed sole napier grass at 8 weeks old, gained 0.4 kg/d (Kariuki et al., 1999) whereas heifers weighing 143 kg liveweight and fed sole napier at 6 weeks old, gained 0.5 kg/d (Kariuki et al., 1998). However, such weight gains may not be achievable in stall-feeding systems where the quality of forage varies widely in nutrient content and digestibility. There is therefore need to develop simulation models to enhance our understanding of the dynamics of nutrient flows which will in turn simplify prediction of heifer weight gain under different nutrient levels and digestibility in the smallholder stall-feeding systems.

## 2.5 Nitrogen metabolism and excretion

Dietary protein that escapes rumen degradation and microbial protein synthesised in the rumen, are used by dairy heifers for maintenance, reproduction and growth. Both of these sources of protein are subsequently hydrolysed in the true stomach and absorbed in the small intestine. There are two types of dietary crude protein: rumen undegraded protein (RUP) and rumen degraded protein (RDP). Ruminal microbes require RDP to meet their N needs. RDP is categorised into non-protein nitrogen (NPN) and true protein. The NPN comprise of ammonia and urea, while true protein comprise of chains of amino acids (AA).

The first step in ruminal protein degradation involves the attachment of bacteria to feed particles, followed by microbial protease activity (Brock et al., 1982). The rate and extent of protein degradation is determined primarily by the proteolytic activity of the rumen microbes and the type of dietary protein (Bach et al., 2005). The peptides and AA resulting from microbial proteolyic activity are then transported into the microbial cell. Inside the cell, peptides can be degraded into AA by peptidases and AA can then be incorporated into microbial protein or further deaminated to branched volatile fatty acids (VFA) , $CO_2$ or ammonia (Tamminga, 1979). If the bacteria are in need of energy, the peptide or AA will be deaminated and the carbon chains will be fermented into branched VFA; however, if adequate energy is available, the AA will be transaminated or used for microbial protein synthesis (Bach et al., 2005).

Fecal nitrogen output is estimated from the sum of three fractions: 1) rumen undegradable and intestinally indigestible dietary N, 2) microbial N that has not contributed to the amino acid pool and 3) endogenous N. Microbial N that does not contribute to the amino acid pool includes nonprotein N (NPN) as well as indigestible true protein. NPN is mainly nucleic acids, which are hydrolysed by nucleases and nucleotidases to nucleotides, purines, pyramidines, phosphoric acid and pentose sugars that are absorbed from the small intestine, metabolized, and excreted in urine. All the pyrimidine N and some of the purine N are metabolized to ammonia or urea and may be excreted in the urine or recycled. The rest of the absorbed purines is excreted in the urine as allantoin and uric acid. In addition, microbial N synthesized in the colon and cecum, is not digested and does not contribute to the amino acid pool, but does form a major part of the fecal N. Much of the N utilized to support microbial fermentation of low-N carbohydrate residues in the hindgut comes from diffusion of urea from the blood with consequent repartitioning of N from urine to feces.

Models of nitrogen metabolism and excretion in dairy heifers include the model by Zanton and Heinrichs (2008) on nitrogen utilisation and excretion, Nennich et al. (2005) on prediction of manure, dry matter, and nutrient excretion, and Marini and Van Amburgh (2005) on nitrogen metabolism, excretion and partitioning between urine and feces. Much as these models are suitable for highly fermentable isocaloric rations, they are inappropriate for smallholder stall-feeding system where energy and then protein are the primary limiting nutritional factors.

## 2.6 Simulation modeling as experimentation

Field experiments are designed to test a few factors that influence the behaviour of a system. However, the number of factors can be so large that the availability of resources to test all factors is quickly overwhelmed, as in the case of farming systems where there is need for a detailed understanding of the interactions between various production systems within a given unit of land (Kebreab et al., 2005). As the complexity of a system increases the value of quantitative systems models also increases (Walker, 1993). Moreover, the results from a single site experiment cannot be transferred to another site and some experiments can take decades before any conclusion can be drawn.

Several types of models are available in animal production varying from simple empirical to complex mechanistic models. Empirical models are where input is directly related to output while mechanistic models require understanding and representing the mechanisms governing animal metabolism (France et al., 1987) and should apply to a wide range of conditions (Baldwin and Miller, 1989).

Sustainability of livestock-forage systems in the tropics requires major improvements in nutrient cycling (Kebreab et al., 2005). Modelling could help identify ways of reducing nutrient losses in livestock-forage systems (Stangel, 1995). Furthermore, computer simulation provides a useful tool for integrating the interacting processes that include forage production, feed intake, nutrient metabolism, urine and manure excretion (Rotz et al., 2005).

In this research therefore, the aim is to develop simulation models that integrate the effects of feed factors on nitrogen partitioning and excretion in manure and urine, that could subsequently lead to better prediction and management of the livestock-forage system.

CHAPTER 3

# Feed resources and manure management in stall-fed dairy cattle in urban and peri-urban Mbarara District

## 3.1 Introduction

The urban and peri-urban areas of Mbarara town, like most other urban and peri-urban areas in Uganda, have experienced increased human population and decreased land for livestock production. Yet the increased human population comes along with increased demand for livestock products and this means readily available market for the livestock products. This has led to the smallholder dairy farmers taking up stall-feeding to meet the increased demand for the products at the same time to increase the household incomes to meet the increased standards of living.

Stall-feeding of exotic dairy cattle was introduced and promoted in Uganda by non-governmental organizations (NGO) and the Uganda government. The NGOs include Send a Cow, World Vision and Heifer Project international (HPI). A survey by MAAIF (1996) of dairy farmers with exotic cross-bred animals showed 46% of these farmers owned 1 or 2 heads of cattle, with most of the farmers practicing cut-and-carry feeding system. A study by MAAIF (1996) found that cut-and-carry feeding system had the highest economic returns compared to other cattle management systems.

Given the high costs of production in this system of intensive stall-feeding, and the need to sustain farm productivity with manure as the only nutrient input to the soil, the issue of sustainability comes to the fore. This study was aimed at understanding the principal attributes of stall-feeding in the urban and peri-urban areas of Mbarara town so as to derive qualitative relationships among system components, and thereby making a detailed study of the system so as to address the issue of sustainability as detailed in the subsequent chapters.

## 3.2 Material and methods

The study site was the urban and peri-urban areas of Mbarara town, and the Participatory Approach as described in Hoang Fagerström et al. (2003) was used. Farmers's records, face-to-face interviews and transect walks were used to collect data at the farm level. Additional data was got from district production offices and service providers. The data at the district production offices had the summaries of production, the number and location of the farmers practicing stall-feeding. There were only 41 farmers and located in the two Divisions of Kamukuzi and Kakoba. Data collection was done from June to November 2006.

The main emphasis of the participatory research was on the inputs, outputs and management practices but some contextual data were also collected to ascertain the role of livestock in the household. Detailed information on size of land, land use, yield of forage and crop residues was gathered. Data on livestock numbers as well as breeds and the time when the farmer started the stall-feeding were recorded. Information on the marketing channels for the produce, as well as the management and application of manure were recorded.

## 3.3 Results and discussion

### 3.3.1 Animals and management system

Herd size and composition, milk production, weaning and mating age categorised by management system are shown in Table 3.1. The farmers practiced both intensive (29.3%) and semi-intensive (70.7%) system of production.

**Table 3.1:** Milk production, herd structure, weaning and mating age by management system

| Parameter | Management system | n[a] | mean | SD | min | max |
|---|---|---|---|---|---|---|
| Milk production (l/d) | Semi-intensive | 25 | 8.00 | 4.10 | 2.00 | 18.00 |
| | Intensive | 11 | 15.73 | 4.82 | 8.00 | 24.00 |
| number of cows | Semi-intensive | 26 | 2.54 | 1.53 | 1.00 | 8.00 |
| | Intensive | 11 | 1.82 | 0.87 | 1.00 | 3.00 |
| Number of heifers | Semi-intensive | 13 | 1.85 | 1.52 | 1.00 | 6.00 |
| | Intensive | 6 | 1.17 | 0.41 | 1.00 | 2.00 |
| number of calves | Semi-intensive | 24 | 1.50 | 0.59 | 1.00 | 3.00 |
| | Intensive | 10 | 1.30 | 0.48 | 1.00 | 2.00 |
| Weaning age (months) | Semi-intensive | 26 | 5.62 | 1.39 | 3.00 | 9.00 |
| | Intensive | 10 | 4.90 | 1.37 | 3.00 | 7.00 |
| Mating age (months) | Semi-intensive | 25 | 24.84 | 5.38 | 18.00 | 36.00 |
| | Intensive | 12 | 23.58 | 3.90 | 18.00 | 30.00 |

[a] Number of respondents

### 3.3.2 Feeds and feeding

Source of water for the animals was National Water tap (85.4% of the farmers), well (9.8% of the farmers), and combination of National water tap and river (4.8% of the farmers). Only 7.3% of the farmers conserved forage in form of hay and silage whereas 92.7% did not. Grass species and the number of farmers that fed the respective grasses are shown in Figure 3.1, major ones being Napier (34.1%), natural (12.2%), combination of napier and natural (43.9%). Legumes fed included *Desmodium spp* (41.5% of the farmers), *Lablab purpureus*, *Calliandra spp* and *Leucaena spp* (2.4% of the farmers each); and *Centrosema spp* and *Glilicidia spp* both fed in combination with other legumes. 34% of the farmers do not feed legumes (Figure 3.2). Banana peels was the most important feed resource among crop residues and agro-industrial by-products. Only 2.4% of the farmers did not feed crop residues and industrial by-products (Figure 3.3). Farmers that had no land for forage were 39% whereas 14.6% had two acres and above, 46.3% had no more than one acre (Figure 3.4). Of the farmers that grew elephant grass, the majority (29.3%) harvested at age of two months (Fig. 3.5), 2.4% harvested depending on availability, 19.5% of the farmers did not feed elephant grass, and 7.3% bought elephant grass.

Napier grass is the dominant forage and is mainly fed as sole feed or in combination with natural pastures. Age at which Napier is harvested was dictated by the demand and the availability.

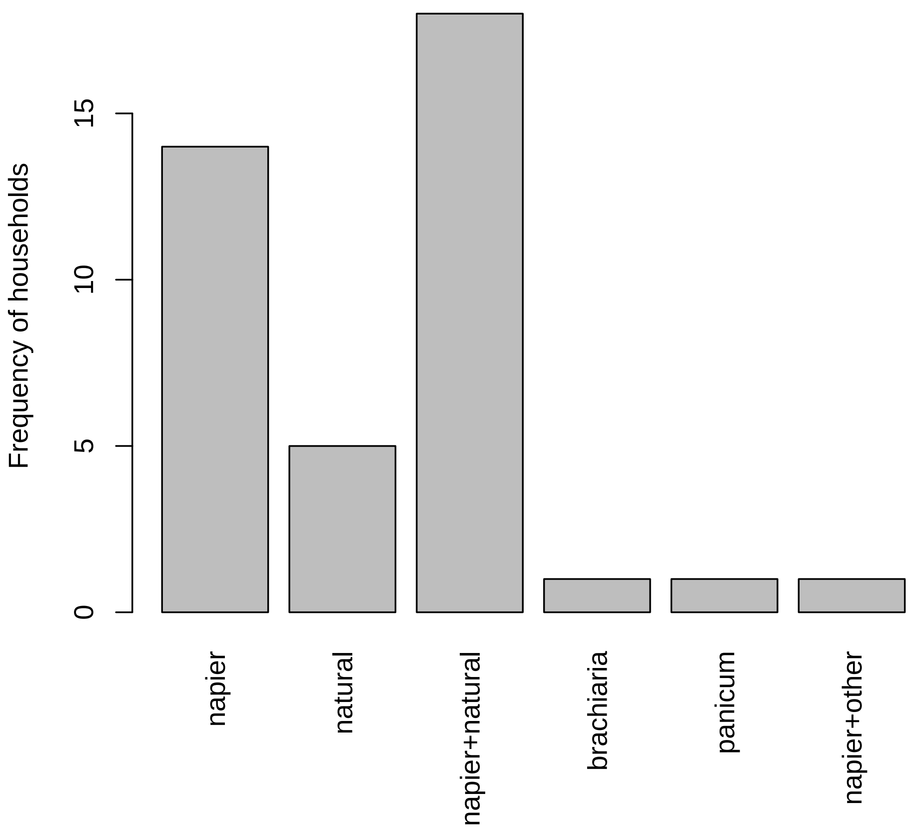



**Figure 3.1:** Grass species fed to dairy cattle; Napier (Napier grass also called elephant grass, *Pennisetum purpureum*), brachiaria (*Brachiaria spp*); panicum (*Panicum spp*); natural refers to grasses commonly available but not cultivated; other refers to any grass that the farmer can find.

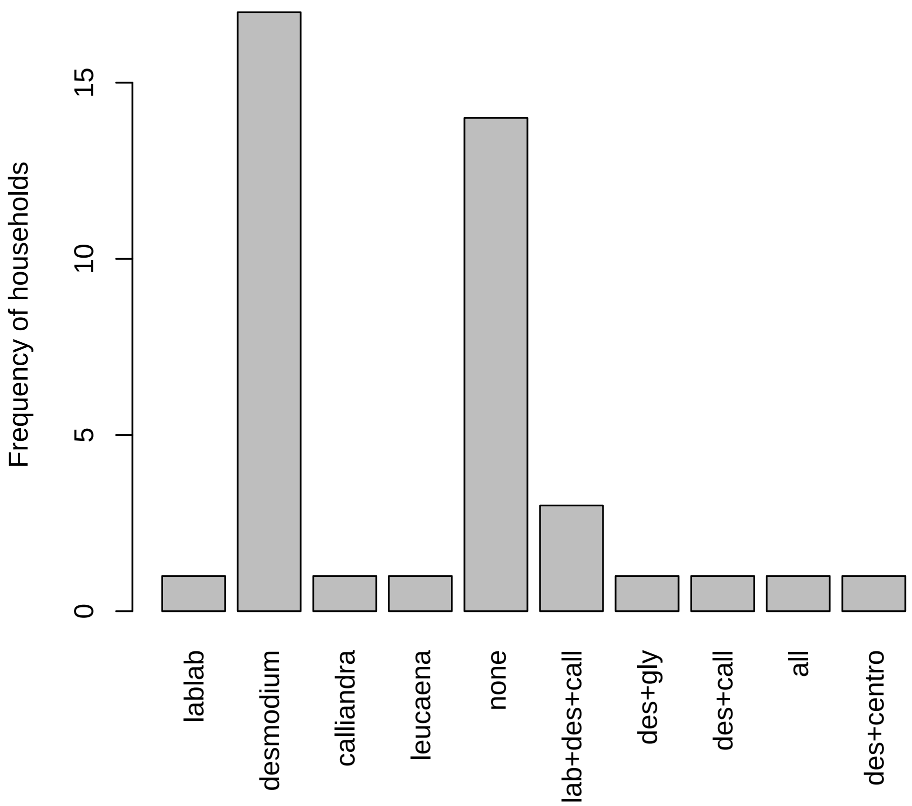



**Figure 3.2:** Legumes species fed to dairy cattle; lab (*Lablab purpureus*); des (*Desmodium spp*); call (*Calliandra spp*); centro (*Centrosema spp*); gly (*Gliricidia spp*).

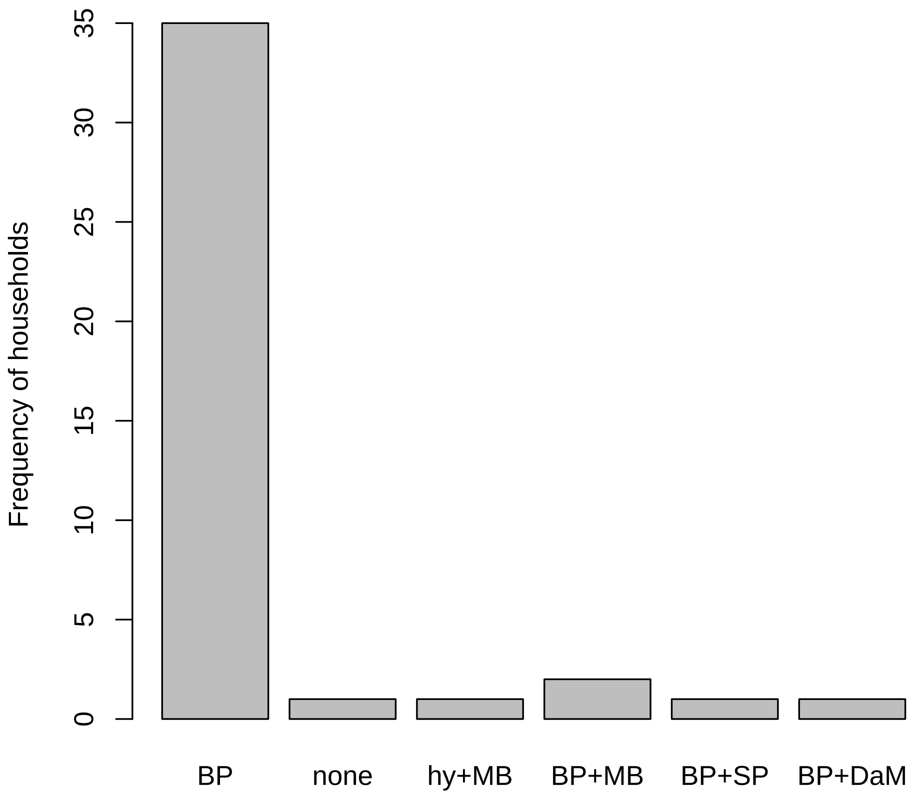



**Figure 3.3:** Crop residues, concentrates and industrial by-products fed to dairy cattle; BP (Banana Peels); hy (hay, combination of any forages available); SP (sweet potato vines); MB (Maize Bran); DaM (Dairy Meal).

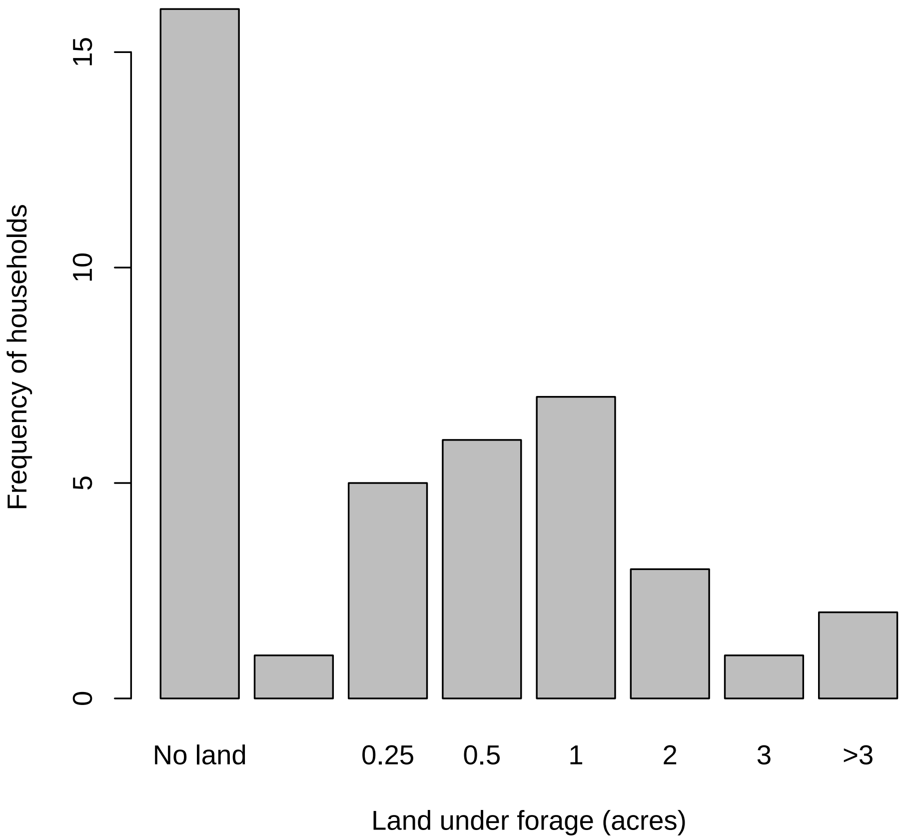



**Figure 3.4:** Acreage available for forage production

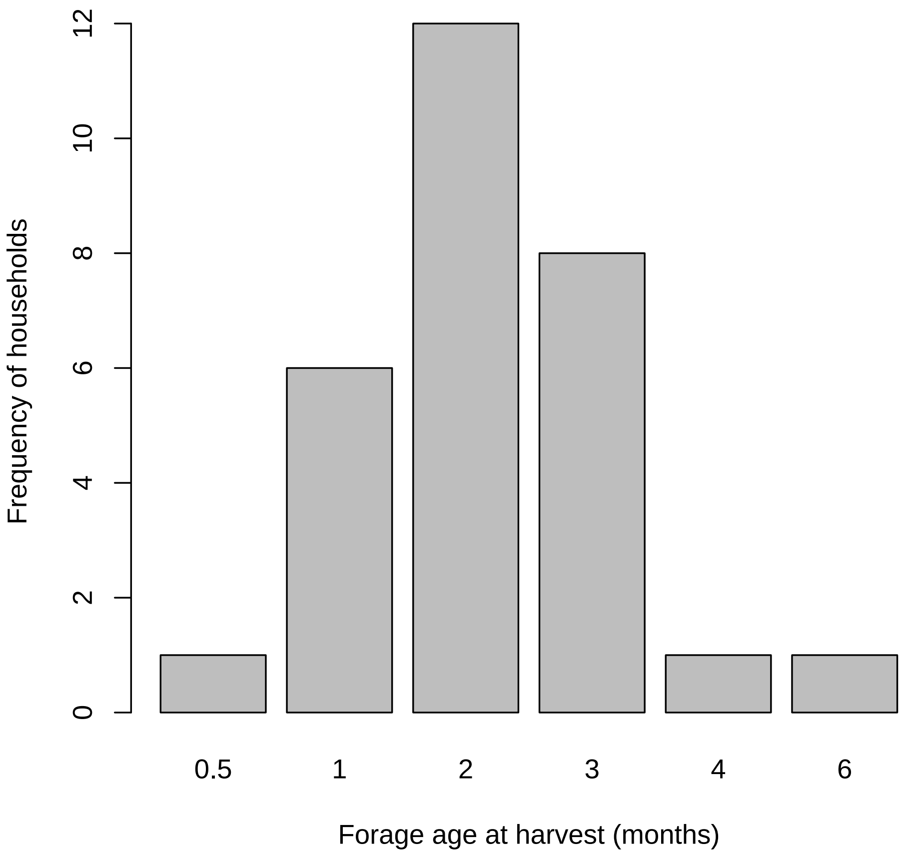



**Figure 3.5:** Age at which elephant grass is harvested for feeding the animals

Although elephant grass is mainly grown on farmers' fields, not all farmers have land where to grow forages. Farmers with no land resort to roadside forages and crop residues especially banana peels. Banana peels are the major crop residue fed. The high percentage of farmers using banana peels is attributed to its status as a staple food of the farmers. Forage legumes are fed as and when they are available. Farmers that feed no legumes include mainly those with no land. Farmers prefer *Desmodium spp* to *Lablab purpureus* because *Lablab purpureus* is labour intensive, has poor tolerance to moisture stress and requires delicate management and handling.

### 3.3.3 Manure management

### Dung management

Manure collected ranged from below ten to over 80 kg/day for individual farmers, with the highest collection in the 10-20kg category (41.5% of the farmers whereas 7.3% of the farmers never collected manure. Manure storage was by surface heaping (58.5% of the farmers), pit (29.2% of the farmers), 2.4% of the farmers used the manure for biogas production and 2.4% gave the manure to neighbours and whoever wanted it. Manure was applied to the fields immediately (4.9% of the farmers), less than one month (9.8%of the farmers), two to three months (31.7% of the farmers), four to six months (12.2% of the farmers) whereas others applied only when they had the time and were convinced that there is need to apply. Figure 3.6 shows the manure application methods. Application methods were surface, covered in trenches, mixed with soil, practiced by 9.8%, 19.5% and 34.1% of the farmers, respectively. Some farmers (7.3%) did not apply manure, 19.5% had no land, and 7.3% sold the manure.

### Urine management

The majority (83%) of the farmers did not collect urine. Collection methods included uncemented pit(12.2% of the farmers), cemented pit (2.4% of the farmers),dung pit(2.4% of the farmers), jerrycans (4.9% of the farmers),biogas pit(2.4% of the farmers) and direct channel to the field(2.4% of the farmers). 78% of the farmers apply urine after four weeks of storage, 2.4% of the farmers

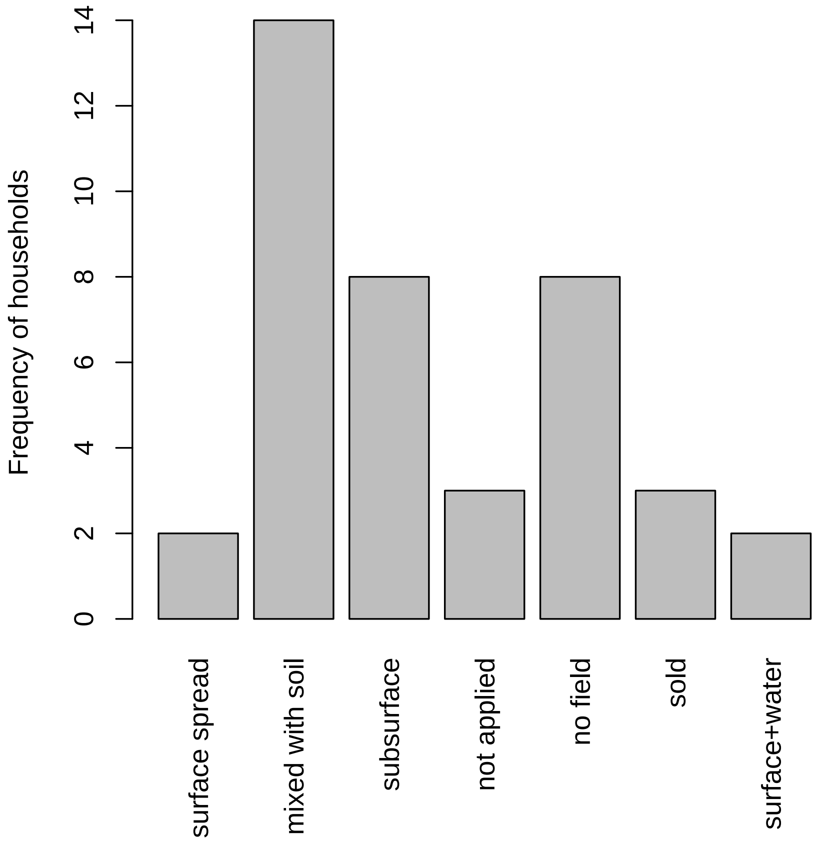



**Figure 3.6:** Method of manure application

apply immediately and the rest apply within one week. Of the farmers that collect urine, 71.4% use surface application and 28.6% use gravitational flow.

## 3.4 Conclusion

Given the findings in this study, specifically age at which forage is harvested, stocking levels, manure management (with respect to collection, handling, application method and timing of application), there are variability in the production and quality of feeds and manure among farm households. This variability is likely to be reflected in the performance of replacement heifers in terms of age at first service, and the resultant milk production potential. These results provide evidence of possibilities of harnessing cattle manure and urine for improved forage production and better animal productivity under zero-grazing.

CHAPTER 4

# Body weight gain of heifers fed on elephant grass under stall-feeding system: A simulation model

## 4.1 Introduction

In Uganda animal agriculture contributes about 17% to the national Agriculture Gross Domestic Product (AGDP) in the form of milk and meat (MAAIF, 2004). Approximately 4% of the cattle population is exotic and crossbred dairy cattle under confined feeding management. Stall-feeding of exotic dairy cattle has gained popularity in Uganda (Kabirizi, 2006), partly it is responsive to government policy on poverty reduction through Uganda's Plan for Modernization of Agriculture (PMA) (UBOS, 2005); and it is attractive to landless poor as an economically feasible source of income and household nutrition security (Nahdy, 2001).

A survey by MAAIF (1996) of dairy farmers with exotic cross-bred animals showed 46% of these farmers owned 1 or 2 heads of cattle, with most of the farmers practicing cut-and-carry feeding system. Although a study by MAAIF (1996) found that stall-feeding had the highest economic returns compared to other cattle management systems, reproductive performance reduce the profitability of smallholder dairy farmers (Nakiganda et al., 2006). For example, the age at first calving in stall-fed dairy cattle, is 2.5 years (Twinamasiko, 2001) as compared to 2 years in the developed world. Although stall-feeding system is based on elephant grass (*Pennisetum purpureum*) as major forage (Muwanga, 1994; Tumutegyereize et al., 1999), because of its high biomass yield compared to other grasses (Boonman, 1993; Anindo and Potter, 1994), little information is currently available on the performance of replacement heifers in napier-based feeding systems under smallholder dairy system in Uganda.

The objective of this part of the study was to develop a model and use it to predict weight gain and recommended weight-for-age at first service of dairy heifers based on forage characteristics, in a stall-feeding dairy system with elephant grass as sole feed.

## 4.2 Materials and methods

This section summarises the procedures, assumptions and equations used to develop a dynamic growth model of dairy heifers from weaning to mating weight, for forage-based stall-feeding in the smallholder dairying system. For the list of symbols used in the text, including description, units of measure, and equation number where first presented, refer to Table 4.2. The prediction equations for energy and protein are based on AFRC (1993) metabolisable energy (ME) and metabolisable protein (MP)system.

### 4.2.1 Feed composition

Nutrient composition, digestibility and degradability parameters are in Table 4.1. However, due to lack of comprehensive nutrient composition data on elephant grass from a single experiment, values from several experiments were pooled to form the basis for parameter estimation.

**Table 4.1:** Nutrient composition, digestibility and degradability of Napier grass[a]

| Age | DM | Ash | DOMD | CP | GE | ADIN | *a* | *b* | *c* | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| | 192 | 159 | 808 | | | | | | | Hassan et al. (1983) |
| | 234 | 152.8 | | 196.9 | | | | | | Hassan et al. (1979) |
| 10 | 182.7 | | | 81.8 | 15.4 | | | | | Muia et al. (2001a) |
| 15 | 238.6 | | | 53.3 | 16.9 | | 213 | 672 | 0.04 | Muia et al. (2001a) |
| 10 | 180 | | | 83 | 16 | | | | | Muia et al. (2001b) |
| 15 | 240 | | | 53 | 17 | | | | | Muia et al. (2001b) |
| 10 | 183.1 | | | 84.1 | 16.1 | | | | | Muia et al. (2000a) |
| 15 | 237.8 | | | 53 | 16.8 | | | | | Muia et al. (2000a) |
| | 176 | | | 68.4 | | | | | | Nyambati et al. (2003) |
| | | 111 | 524 | 115.4 | | 1.3 | 211 | 541 | 0.03 | Kabi et al. (2005) |
| | 155 | | 571 | 118 | | | | | | Kariuki et al. (1998) |
| M[b] | | 136 | 560 | 61 | 15.6 | | | | | Mlay et al. (2006) |
| 6-8 | | 124.9 | 692 | 102.5 | | | | | | Mpairwe et al. (1998) |

[a] Age in weeks, Ash in g/kgDM, DM = dry matter (g/kg); DOMD = digestible organic matter (g/kgDM); CP = crude protein (g/kgDM); ADIN = acid detergent insoluble nitrogen (g/kgDM); GE = gross energy (MJ/kgDM); *a* = water soluble fraction (g/kgCP); *b* = potentially degradable nitrogen other than water soluble fraction (g/kgCP); *c* = degradation rate per hour of the *b* fraction (g/kgCP)

[b] M refers to mature, no specific age given

### 4.2.2 Energy value of feed

The energy value of feed is estimated as follows:

$$ME\,(MJ/kgDM) = 0.0157 \times DOMD\,(g/kgDM) \tag{4.2.1}$$

where ME is metabolisable energy; DOMD is Digestible Organic Matter in a feed, and is estimated as

$$DOMD = OMD \times (1000 - total\,ash)/1000 \tag{4.2.2}$$

where OMD is Organic Matter Digestibility (g/kg)

$$FME = ME \times \left(0.467 + 0.00136 \times ODM - 0.00000115 \times ODM^2\right) \tag{4.2.3}$$

where FME (MJ/kgDM) is fermentable metabolisable energy; ODM is Oven Dry Matter content (g/kg)

### 4.2.3 Protein value of feed

Estimation of the Metabolisable Protein (MP) from Crude Protein (CP) involves the following calculations. Definitions of symbols used are in Table 4.2.

$$UDP = CP - \{QDP + SDP\} \tag{4.2.4}$$

$$SDP = \{(b \times c)\,/\,(c + r)\} \times CP \tag{4.2.5}$$

$$QDP = a \times CP \tag{4.2.6}$$

where $r$ is calculated as follows

$$r = -0.024 + 0.179\left\{1 - e^{(-0.278L)}\right\} \tag{4.2.7}$$

where $L$ is level of feeding as a multiple of MJ of ME for maintenance.

$$MCP = FME \times y \tag{4.2.8}$$

where $y$ is microbial protein yield in the rumen (gMCP/MJ of FME), and is calculated as

$$y = 7.0 + 6.0\left\{1 - e^{(-0.35L)}\right\} \tag{4.2.9}$$

$$DUP = 0.9\{UDP - 6.25ADIN\} \tag{4.2.10}$$

$$DMTP = 0.6375MCP \tag{4.2.11}$$

$$MP(g/d) = 0.6375MCP + DUP \tag{4.2.12}$$

$$ERDP = 0.8QDP + SDP \tag{4.2.13}$$

If ERDP supply is less than (or equal to) ERDP required, then

$$MCP(g/d) = ERDP(g/d) \tag{4.2.14}$$

Else

$$MCP\,(g/d) = FME\,(MJ/d) \times y\,(gMCP/MJ\,FME) \tag{4.2.15}$$

**Table 4.2:** List of symbols used in the text, including description, units of measure, and equation number where first presented

| Symbol | Definition | Units | Eq no. |
|---|---|---|---|
| $a$ | Proportion of water soluble Nitrogen in the total Nitrogen of a feed | Unit-less | (4.2.6) |
| ADIN | Acid detergent insoluble nitrogen in a feed | g/kgDM | (4.2.10) |
| B | Derived parameter to predict energy retention | Unit-less | (4.2.20) |
| $b$ | Proportion of potentially degradable N other than water soluble N of a feed | Unit-less | (4.2.5) |
| $c$ | Fractional rumen degradation rate per hour of the $b$ fraction of feed N | Unit-less | (4.2.5) |
| $C_1$ | Correction factor for $MP_f$ for heifers | Unit-less | (4.2.19) |
| $C_2$ | Correction factor for ME for heifers(1.1) | Unit-less | (4.2.26) |
| $C_3$ | Correction factor for mature body size and sex of animal(1.0-1.3) | Unit-less | (4.2.28) |
| $C_4$ | Correction factor for plane of nutrition ($L$), 1 if $L>1$, 0 if $L<1$ | Unit-less | (4.2.28) |
| CP | Crude protein in of a diet or in a feed | g/kgDM, g/d | (4.2.4) |
| DMI | Dry matter intake | kg/d | (4.2.16) |
| DMTP | Digestible microbial true protein (= metabolizable protein from microbes) | g/d, g/kgDM | (4.2.11) |
| DOMD | Digestible organic matter | kg/d, g/kgDM | (4.2.1) |
| DUP | Digestible undegraded protein (N x 6.25) | g/kgDM, g/d | (4.2.10) |
| $E_m$ | Net energy for maintenance | MJ/d | (4.2.20) |
| $E_f$ | Net energy retained in a growing animal | MJ/d | (4.2.26) |
| ERDP | Effective rumen degradable dietary protein | g/d, g/kgDM | (4.2.13) |
| $EV_g$ | Energy value of tissue gained or lost | MJ/kg | (4.2.26) |
| F | Fasting metabolism | MJ/(kg fasted weight)$^{0.67}$ | (4.2.21) |
| Fa | Available forage | kg/d | (4.2.17) |
| FME | Fermentable metabolizable energy of a diet | MJ/d, MJ/kgDM | (4.2.3) |
| GE | Gross energy of a diet | MJ/d, MJ/kgDM | NA |
| k | Efficiency of utilisation of metabolisable energy for a given metabolic process | Utit-less | (4.2.20) |
| $k_m$ | Efficiency of utilisation of metabolisable energy for maintenance | Unit-less | (4.2.22) |
| $k_f$ | Efficiency of utilisation of metabolisable energy for weight gain | Unit-less | (4.2.22) |
| L | Level of feeding as a multiple of MJ of ME for maintenance | Unit-less | (4.2.7) |
| $M_{mp}$ | Metabolisable energy requirement for maintenance and production | MJ/d | (4.2.20) |

Continued on Next Page...

Table 4.2 – Continued

| Symbol | Definition | Units | Eq no. |
|---|---|---|---|
| M/D | Metabolisable energy | MJ/kgDM | (4.2.16) |
| MCP | Microbial crude protein supply | g/d, g/kg | (4.2.8) |
| ME | Metabolisable energy | MJ/d, g/KgDM | (4.2.1) |
| MER | Metabolisable energy requirement | MJ/d | (4.2.16) |
| MP | Metabolizable protein | g/d, g/kgDM | (4.2.12) |
| $MP_m$ | Metabolisable protein requirement for maintenance | g/d | (4.2.18) |
| $MP_f$ | Metabolisable protein requirement for liveweight gain | g/d | (4.2.19) |
| ODM | Oven dry matter content | g/kg | (4.2.3) |
| OMD | Organic matterdigestibility | g/kg | (4.2.2) |
| $q_m$ | Metabolisability of gross energy at maintenance | Unit-less | (4.2.24) |
| QDP | Quickly degradable protein (N x 6.25) of a diet or in a feed | g/d, g/kgDM) | (4.2.4) |
| R | Energy retention, scaled by fasting metabolism | Unit-less | (4.2.20) |
| $r$ | Rumen digesta fractional outflow rate per hour | Unit-less | (4.2.5) |
| SDP | Slowly degradable protein (N x 6.25) of a diet or in a feed | g/d, g/kgDM | (4.2.4) |
| UDP | Undegradable dietary protein (N x 6.25) of a diet or in a feed | g/kgDM | (4.2.4) |
| W | Live weight of the animal | kg | (4.2.17) |
| $y$ | Microbial protein yield in the rumen | gMCP/MJ of FME | (4.2.8) |

### 4.2.4 Estimation of intake

According to AFRC (1993) the dry matter intake (DMI) is estimated as follows:

$$DMI\,(kg/d) = MER/(M/D) \tag{4.2.16}$$

where MER is metabolisable energy requirement (MJ/d), M/D is metabolisable energy (MJ/kgDM). This estimation of DMI is appropriate where daily gain is predetermined. In a case where the DMI depends on forage availability and daily gain is not known forehand, the intake can be estimated based on experimental observations. An estimate of 2.7% of body weight based on Kariuki et al. (1998) value of 2.94%, Diaz-Solis et al. (2006) value of 2.54% and Blomquist (2005) value of 2.5-3.0% of the body weight was used. Therefore

$$IF \quad Fa \geq 0.027 * W, \quad THEN \quad DMI = 0.027 * W, \quad ELSE \quad DMI = Fa \tag{4.2.17}$$

where $Fa$ is available forage.

### 4.2.5 Protein requirements

Metabolizable protein requirement for maintenance (kg/d) is estimated as

$$MP_m = 2.30W^{0.75} \tag{4.2.18}$$

Metabolizable protein requirement for growth (g/d) is estimated as

$$MP_f = C_1 \left\{168.07 - 0.16869W + 0.0001633W^2\right\} \times \{1.12 - 0.1223\Delta W\} \times 1.695\Delta W \tag{4.2.19}$$

where $MP_f$ is metabolizable protein requirement for liveweight gain (g/d), $C_1$ is a correction factor ranging from 0.8 – 1.0, $W$ is liveweight of the animal (kg).

### 4.2.6 Energy requirements

The energy requirement is calculated as follows:

$$M_{mp}(MJ/d) = (E_m/k) \times \ln\{B/(B-R-1)\} \tag{4.2.20}$$

where $M_{mp}$ is ME requirement for both maintenance and production, $E_m$ (MJ/d) is the sum of animal's fasting metabolism $(F)$ and activity allowance ($A$ = $0.0071W)$ for zero-grazed heifers, $R$ is the scaled energy retention. The fasting metabolism, MJ/(kg fasted weight)$^{0.67}$, is defined as

$$F = 0.53\,(W/1.08)^{0.67} \tag{4.2.21}$$

The factors $B$ and $k$ are calculated from the efficiencies of utilization of ME as follows:

$$B = \frac{k_m}{\left(k_m - k_f\right)} \tag{4.2.22}$$

$$k = k_m \times \ln\left(k_m/k_f\right) \tag{4.2.23}$$

where $k$ is the efficiency of utilization of ME (Metabolizable Energy) for a given metabolic process, $B$ is a derived parameter to predict energy retention, $k_m$ is the efficiency of utilization of ME for maintenance, $k_f$ is the efficiency of utilization of ME for weight gain. Both $k_m$ and $k_f$ can be calculated as follows:

$$k_m = 0.35q_m + 0.503 \tag{4.2.24}$$

$$k_f = 0.78q_m + 0.006 \tag{4.2.25}$$

where $q_m$ is the metabolizability of [GE] at maintenance, [ME]/[GE], where GE is the gross energy of a diet (MJ/d or MJ/kgDM).

Scaled energy retention $(R)$ is calculated from

$$E_f = C_2\,(EV_g \times \Delta W) \tag{4.2.26}$$

where $C_2$ is the correction factor for ME for heifers ( 1.1 ) and then:

$$R = \frac{E_f}{E_m} \tag{4.2.27}$$

where $E_f$ is Net Energy retained in growing animal (MJ/d), $E_m$ is Net Energy for maintenance (MJ/d).

### 4.2.7 Predicting live weight gain

Predicting live weight gain involves the following steps:

***Step 1.*** *Energy Value of weight gain*

This is given by the expression

$$EV_g = \frac{C_3\left(4.1 + 0.0332W - 0.000009W^2\right)}{(1 - C_4 \times 0.1475\Delta W)} \tag{4.2.28}$$

where $EV_g$ is energy value of tissue gained (MJ/kg), $\Delta W$ is live-weight change (kg/d), $C_3$ is a correction factor (range 1.00 – 1.30) for mature body size and sex of animal; $C_4$ is a correction factor for plane of nutrition ($L$), 1 when $L > 1$ and 0 when $L < 1$. These correction factors are given in AFRC (1993).

***Step 2.*** *Energy retention*

Scaled energy retention ($R$) is as defined in equation (4.2.27).

***Step 3.*** *Metabolisable Protein requirement for growth*

Equation (4.2.19) is rearranged to estimate weight gain based on $MP_f$.

***Step 4.*** *Weight gain*

Equation (4.2.26) is rearranged to give

$$\Delta W = \frac{E_f}{(C_2 \times EV_g)} \tag{4.2.29}$$

By combining the two equations (4.2.28) and (4.2.29) that contain the term $\Delta W$, we get

$$\Delta W = \frac{E_f}{\left(C_2 X + 0.1475 E_f\right)} \tag{4.2.30}$$

where $X = C_3\left(4.1 + 0.0332W - 0.000009W^2\right)$ is taken from equation (4.2.28)

## 4.3 Description of the simulation model and the data used

### 4.3.1 Description of the simulation model

In this study it is assumed that the animal is not constrained in any other way apart from the supply of crude protein and energy. Holstein Friesian heifers of less than 1 year and weighing less than 150 kg of bodyweight at the start of the simulation are used in this model. The feed input parameters are DM, OMD, GE, ash, CP, CP degradation variables (*a, b, c*, see Table 4.2 for definitions), acid detergent insoluble nitrogen (ADIN). Animal characteristics are initial weight and level of feeding. The dry matter intake is set at 2.7% of animal's weight as explained in Subsection 4.2.4. All other parameters are calculated by the model. If effective rumen degradable protein (ERDP) supply is less than (or equal to) ERDP required, then microbial crude protein (MCP) is equal to ERDP else MCP is equal to fermentable metabolisable energy (FME) multiplied by microbial protein yield (*y*).

The simulation model is coded in VENSIM® 5.5 (The Ventana Simulation Environment, Ventana Systems, Inc.), based on differential equations with a 1-day time step ($\Delta$t = 1 day). Figure 4.1 shows the simulation logic of the model. After part of ME and MP have been used for maintenance, daily gain (DG) is dependent on the balance between Metabolisable Energy for growth (MEg) and Metabolisable Protein for growth (MPg); if potential growth due to metabolisable protein (Gp) is greater than the potential growth due to metabolisable energy (Ge), then MEg is considered limiting and the growth is determined by Ge. Else if potential growth due to metabolisable protein (Gp) is less than potential growth due to metabolisable energy (Ge), then MPg is considered limiting and the growth is determined by Gp. The simulated DG is then added to the weight to get a new weight (W), and the process is repeated for the desired number of days.

### 4.3.2 Description of the data sets used in calibration and evaluation

The experiments from which these datasets (Table 4.3) were generated were either on the effect of supplementation on degradability (Kabi et al., 2005; Kariuki et al., 1998; Muia et al., 2001b) or effect of supplementation on weight gain (Kariuki et al., 1999, 1998; Muia et al., 2000a). Degradability parameters required as inputs for the simulation model were obtained from experiments that fall in the degradation category. For growth experiments, only the controls (where the basal diet was only elephant grass) were used as data sources for the simulation model.

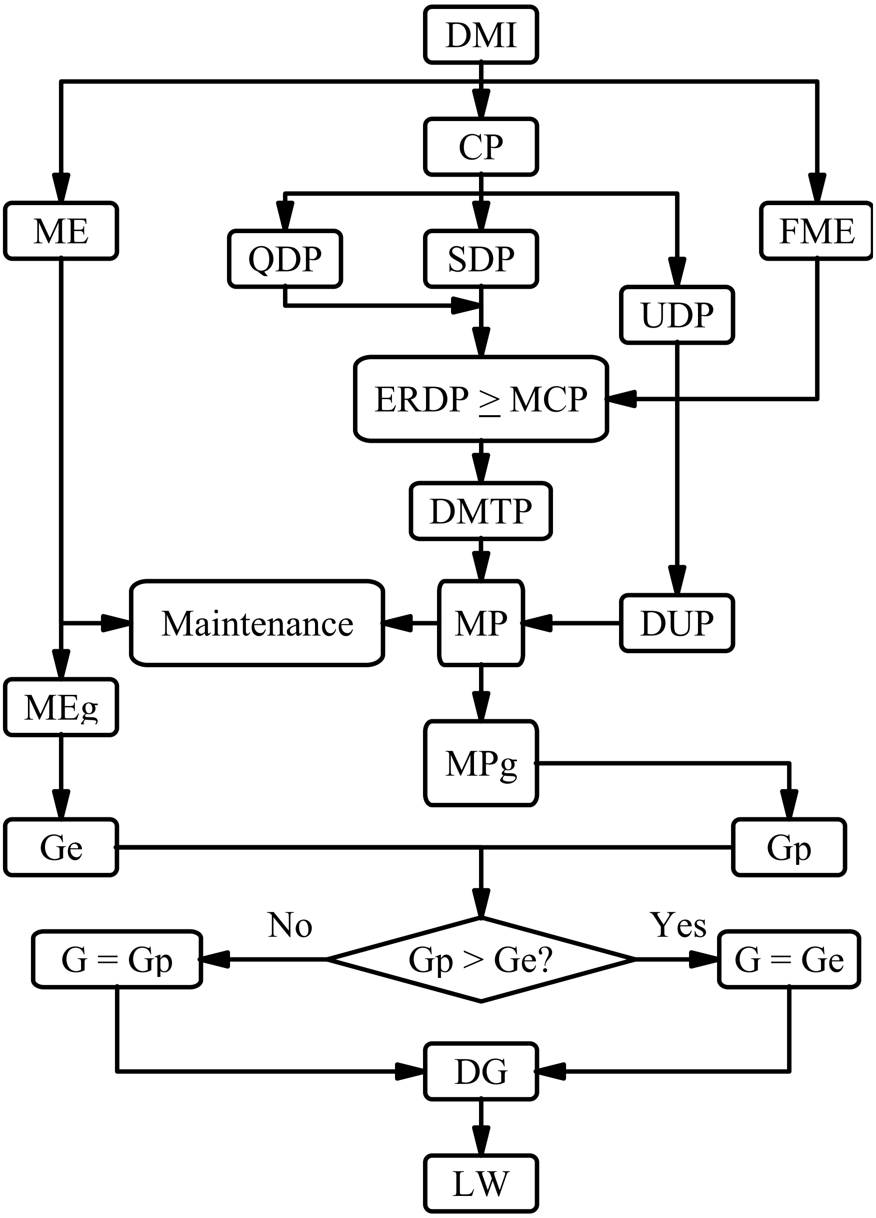



**Figure 4.1:** Simulation logic of the weight gain of heifers fed on napier grass. For definitions of the parameters refer to Table 4.2 and Subsection 4.3.1

**Table 4.3:** Chemical composition of the forage used in model development and evaluation[a]

| DM | CP | Ash[b] | $a$ | $b$ | $c$ | ADIN | GE | Age | References |
|---|---|---|---|---|---|---|---|---|---|
| *Model development* | | | | | | | | | |
| - | - | 111 | 0.2468 | 0.4942 | 0.02 | 1.3 | - | 1 m | Kabi et al. (2005) |
| 176 | 68.4 | - | - | - | - | - | - | 1-1.5 m | Nyambati et al. (2003) |
| 183 | 84 | - | - | - | - | - | 16.1 | 10 wks | Muia et al. (2000a) |
| *Model evaluation* | | | | | | | | | |
| - | - | - | 0.213 | 0.672 | 0.04 | - | 16 | 10 wks | Muia et al. (2001a) |
| 155 | 118 | 204 | - | - | - | - | - | 6 wks | Kariuki et al. (1998) |
| - | 115.4 | - | 0.211 | 0.541 | 0.03 | - | - | 1 m | Kabi et al. (2005) |

[a] DM, CP, Ash and ADIN in g/kgDM; $a$, $b$ and $c$ are proportions; GE in MJ/kgDM; Age in weeks (wks) or metres (m)
[b] Where DOMD is not known, then Ash is used according to equation (4.2.2).

### 4.3.3 Model calibration

According to AFRC (1993) the proportion of DUP in UDP varies from nil to 0.9, depending on the feed, its composition and pretreatment. Parameters that describe protein degradation in the rumen ($a$, $b$, $c$), and ADIN which contributes directly to fecal N levels, are highly variable (Webster, 1993) even when determined for the same samples at different laboratories. Therefore these parameters were selected as the starting point for the calibration. We used the values of Table 4.3 for calibration. Although the calibration datasets are the same ones used to derive parameters for the model, they provide an indication of the ability of the model to predict daily gain following manipulation of model parameters to improve accuracy (Hill et al., 2006).

## 4.4 Results and discussion

### 4.4.1 Model evaluation

The simulation model produced results similar to those observed in field studies (Table 4.4). Simulated DG of 0.51 kg was close to the DG of 0.50 reported by Kariuki et al. (1998). Simulated (4.58 kg/d) and observed (5.00 kg/d) DMI were close and so were simulated (0.54 kg/d) and observed (0.59 kg/d) CPI.

From the data used to develop and evaluate the model it was not possible to compare the model's predicted growth curve with observed curve; this was because only averages were given in the observed data. Nonetheless, to appreciate the structure of the simulated curve, we compared the simulated growth curve to that of Kertz et al. (1998) and the fitted growth curve by Koenen and Groen (1996) as shown in Figure 4.2.

From the graph it is observed that the simulated body weight is low compared to that of Kertz et al. (1998), and the fitted growth curve by Koenen and Groen (1996). The difference can be explained by the differences in the feeding. For Koenen and Groen (1996) the data used for fitting the growth model was from heifers fed concentrate, hay, pasture and grass silage for *ad libitum* intake; thus the maximum growth rate of Von Bertalanffy curve equaled 0.8 kg/d and was reached at 212 days

**Table 4.4:** Predicted and observed DG, DMI and CPI for heifers weighing 143 kg and fed for 104 days

| **Forage** | **DG**[a] | **W**[b] | **DMI**[a] | **CPI**[a] | **Time**[a] | **References** |
|---|---|---|---|---|---|---|
| Elephant grass, | 0.50 | 143.30 | 5.00 | 0.59 | 104 | Observed[c] |
| 6 weeks old | 0.51 | 143.30 | 4.58 | 0.54 | 104 | Predicted |

[a] DMI, CPI, DG in kg/d; Time in days.
[b] W=initial weight in kg
[c] Kariuki et al. (1998)

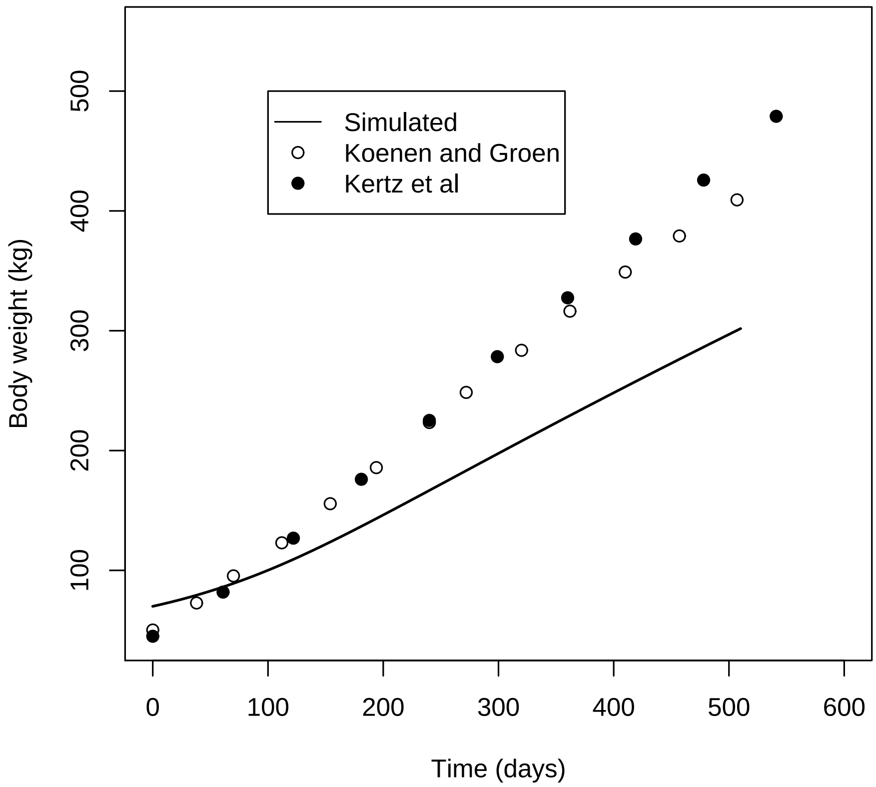



**Figure 4.2:** Comparison of model body weight output with observed and fitted values

of age. For Kertz et al. (1998) grower concentrate, alfalfa hay and grass hay were given to the experimental heifers; this made it possible to attain post-weaning daily body weight gain of 0.82 to 0.93 kg.

### 4.4.2 Model use

From Table 4.1 the concentration of crude protein in elephant grass can be as low as 53 g/kg DM and as high as 196.9 g/kg/DM. Based on these values we used the simulation model to predict corresponding increase in DG (Table 4.5).

**Table 4.5:** Predicted daily gain of a 70 kg heifer, and days to target weight of 300 kg as a function of CP of the forage[a]

| CP | 50.00 | 75.00 | 100.00 | 125.00 | 150.00 | 175.00 | 200.00 |
|---|---|---|---|---|---|---|---|
| DG | -0.01 | 0.17 | 0.34 | 0.50 | 0.66 | 0.81 | 0.94 |
| Days | - | 1073 | 653 | 458 | 343 | 275 | 229 |

[a] DG in kg/day; CP in g/kgDM

The predicted loss in weight of 0.01 kg/day at 50 g/kgDM reflects sub-optimal supply of CP to meet maintenance requirements. From Table 4.5 it is possible to achieve higher growth rates and consequently reduce on the number of days taken to target weight for mating of the heifers by feeding forage high in CP. DM digestibility and CP content (Ogwang and Mugerwa, 1976) and rumen degradation (Muia et al., 2001b) of elephant grass decline with age. This decline is mainly due to increase in acid detergent fibre (ADF), neutral detergent fibre (NDF) and acid detergent lignin (ADL) and a decrease in CP content (Minson, 1990). It is therefore apparent that feeding elephant grass when CP is high could result in better performance.

According to the MLD (1991) recommendations in the smallholder dairy systems, the weaning weight for dairy heifers is 70 kg and a target of 300 kg to be attained by 18 months of age for first service. For this target to be met the heifers are assumed to gain at least 0.5 kg per day. The model was used to predict how long the heifer takes to attain the above target. The forage characteristics used as inputs were based on elephant grass at 6 weeks. From the simulation model, even with high levels of CP (118 g/kgDM) reported by Kariuki et al. (1998), the average growth rate was 0.454

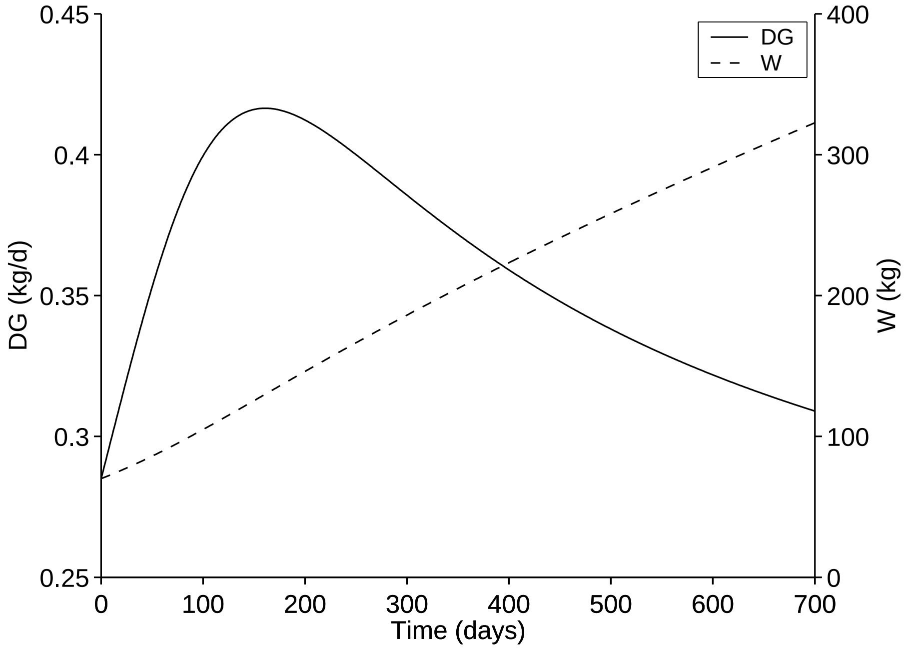



**Figure 4.3:** DG and W at CP 80 g/kgDM and ME 14.14 MJ/kgDM

kg/d and the time taken to reach the 300 kg target was 507 days (Table 4.5) instead of 460 days. This is 0.5 months shorter than observed in zero grazing smallholder dairy systems in Uganda as reported by Twinamasiko (2001). This means that heifers fed on elephant grass as a sole feed are unlikely to attain the target weight for service in record time. However, it is important to note that there was lack of data to test the model from 70 kg to 300 kg; the model was evaluated for heifers of initial weight 143 kg growing to 196 kg.

In Figure 4.3, daily gain increases from the start of the simulation to 150 days and declines thereafter. This pattern of high growth rate in early stages of life, followed by a continuous slow increase as the animal gets older is well established (Vaccaro and Rivero, 1985) and is due to lower maintenance requirements at smaller W (Kertz et al., 1998). The curve for W is similar to that obtained by (Koenen and Groen, 1996). Figure 4.4 shows the output where CP is limiting growth. Higher ME level led to higher DG and reduction in days to attain 300 kg. Increased CP level in forage led to higher growth rate and reduced time to target mating weight. However, when CP exceeded 110 g/kgDM, growth was limited by ME.

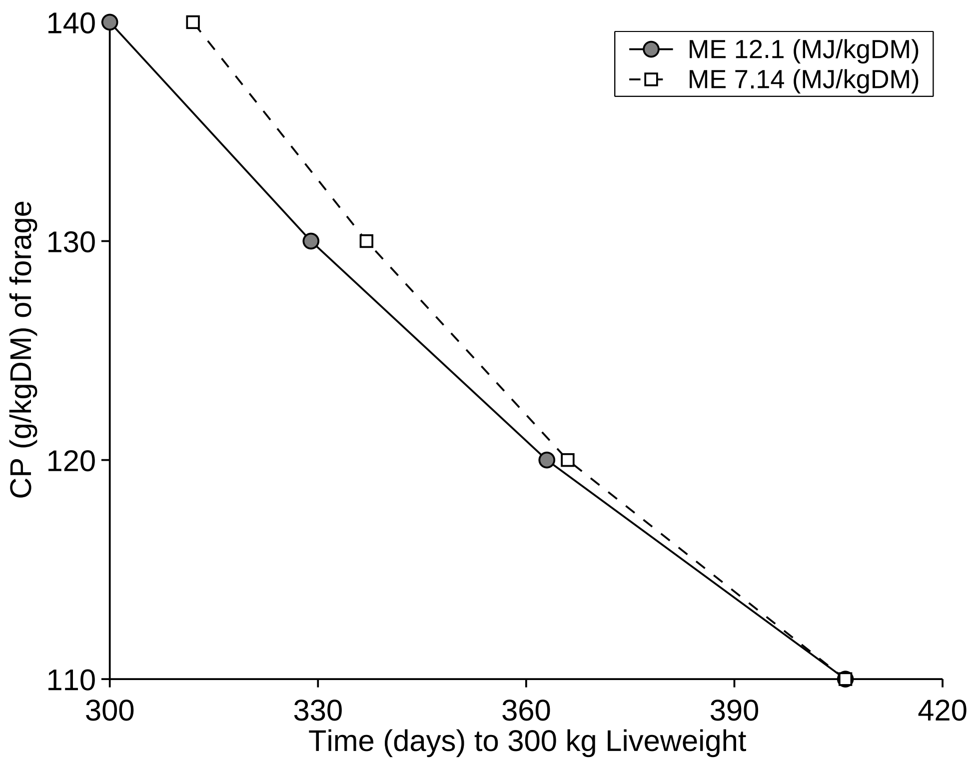



**Figure 4.4:** Effect of CP on time to target mating W of 300 kg at two levels of ME

## 4.5 Conclusion

In conclusion, this study has shown that growth rate of dairy heifers fed elephant grass as sole feed can be predicted based on forage characteristics. It indicates that when Elephant grass is the sole feed, increased CP intake leads to higher weight gain, and that ME is limiting if forage CP exceeds 110 g/kgDM. From the study, it is also clear that heifers fed elephant grass as sole feed are unlikely to attain the recommended mating weight in the recommended time. Although the model predictions were similar to field results, the model has limitations in that only the averages for the observed values were available for its development and evaluation of the model. Furthermore, due to lack of relevant data the model was evaluated for heifers with initial weight of 143 kg for growth up to 196 kg. Therefore further research on heifer performance in smallholder dairy is needed to accumulate adequate data both for developing and evaluating the simulation models of heifer growth. Nonetheless, results of this study are valuable in that being able to predict the growth of heifers can be crucial in providing insight for appropriate management intervention.

CHAPTER 5

# Modelling the effect of supplementing elephant grass with *Lablab purpureus* and *Desmodium spp* on weight gain of dairy heifers under stall-feeding system

## 5.1 Introduction

Because of the importance of stall-fed dairy cattle to poverty reduction programs in Uganda, farmers require a sustainable source of replacement stock to sustain the industry. Good nutrition is a pivotal input for raising replacement heifers to target weight for mating at 24–28 months (MLD, 1991). This is rarely achievable with the variability in quality of Napier (Muia et al., 1999; Ogwang and Mugerwa, 1976) that dominate feed resource base of intensive dairy systems in Uganda. The energy content in Napier is considered to be adequate to sustain acceptable growth of replacement heifers (Muia et al., 2000b); while proteins are most limiting in tropical forages (Freer et al., 1997). However previous models in this study suggested that energy becomes a limiting nutrient when protein content of Napier exceeds 110 g/KgDM. This observation compares favorably with the threshold level of 120g CP/kgDM for moderate production of dairy cattle (ARC, 1984). However, Kariuki et al. (1999) recorded increased growth of heifers when Napier grass (117g CP/kgDM) was fed together with legume supplements. This suggests that additional factors to energy limitations affect animal performance at the threshold CP levels in Napier grass. Guidelines for appropriate level for legume supplementation for optimal heifer growth are not available.

The objective of this research was to study the effect of supplementing elephant grass at different levels of CP with *Lablab purpureus* and *Desmodium spp* on daily gain in dairy heifers, using the simulation model of heifer growth developed in Chapter 4, in a stall-feeding dairy system.

## 5.2 Materials and methods

This section summarises the procedures, assumptions and equations used to develop a dynamic growth model of dairy heifers from weaning to mating weight, for elephant grass supplemented with *Lablab purpureus* and *Desmodium spp* in a smallholder stall-feeding dairying system. The procedures, equations and definitions are as given in Chapter 4, Section 4.2, from Subsection 4.2.2 to Subsection 4.2.7. The prediction equations for energy and protein are based on AFRC (1993) metabolisable energy (ME) and metabolisable protein (MP) system.

### 5.2.1 Feed composition

Feed parameters of elephant grass, *Lablab purpureus* and *Desmodium spp* are given in Table 4.1, Table 5.1 and Table 5.2 respectively.

**Table 5.1:** Chemical composition, Energy and crude protein degradation of lablab[a]

| DM | CP | OMD | Ash[b] | GE | ADIN | *a* | *b* | *c* | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | 170 | 560 | | | | | | | Murphy and Colucci (1999) |
| | 157 | | | | | 0.237 | 0.691 | 0.105 | Mpairwe et al. (2003a) |
| | | | | | | 0.244 | 0.676 | 0.153 | Mpairwe et al. (2003b) |
| | 158 | 597 | | | | | | | Kabirizi (2006) |
| | 163 | | | | | | | | Nyambati et al. (2003) |
| | 180 | | 119.4 | | | 0.2479 | 0.6363 | 0.14 | Melaku et al. (2003) |
| 215 | 198 | | 115.0 | | | | | | Linga et al. (2003) |
| | 254 | | 114.0 | | 2.44 | | | | Mupangwa et al. (2006) (8wks) |
| | 216 | | 114.0 | | 0.71 | | | | Mupangwa et al. (2006) (14wks) |
| 170 | 174 | | | | | | | | Mbuthia and Gachuiri (2003) |
| | 191.8 | | | 13.16 | | | | | Nworgu and Ajayi (2005) |
| | 128 | | 129 | | | | | | Osuhor et al. (2004) |
| | | | | | 1.26 | | | | Mupangwa et al. (2003) |

[a] DM, Ash, CP, ADIN in g/kgDM; GE in MJ/kgDM; Age in weeks
[b] Where DOMD is not known, then Ash is used according to equation 4.2.2.

**Table 5.2:** Nutrient composition and digestibility, degradability, energy and age of *Desmodium spp*[a]

| Species | DM | CP | OMD | Ash[b] | GE | ADIN | *a* | *b* | *c* | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| *D.intortum* | | 120 | | 87 | | | | | | Nurfeta et al. (2008) |
| *D.uncinatum* | | | | 84.3 | | | 0.311 | 0.414 | 0.065 | Baloyi et al. (2008) |
| *D.uncinatum* | 270 | | 496 | 40 | | | | | | Milford (1967) |
| *D.intortum* | 486 | 105 | | | 15.0 | | | | | Aregheore et al. (2006) |
| *D.intortum* | | 118.1 | | 55.1 | | | 0.214 | 0.216 | 0.0 2 | Mghen et al. (1996) |
| *D.ucinatum* | | 163.1 | | 85.1 | | | 0.291 | 0.423 | 0.0 24 | Mghen et al. (1996) |
| *D.intortum* | | 229.4 | | | 20.47 | | | | | Stobbs (1971) |
| *D.intortum* | | 199 | | 98 | | | | | | Getachew et al. (2000) |
| *D.uncinatum* | | 134.5 | 642.9 | 104 | | 2.6 | | | | Jingura et al. (2001) |

[a] DM = dry matter (g/kg); DOMD = digestible organic matter (g/kgDM); CP = crude protein (g/kgDM); ADIN = acid detergent insoluble nitrogen (g/kgDM); GE = gross energy (MJ/kgDM); *a* = water soluble fraction; *b* = potentially degradable nitrogen other than water soluble fraction; *c* = degradation rate per hour of the *b* fraction

[b] Where DOMD is not known, then Ash is used according to equation 4.2.2.

## 5.3 Description of the simulation model

It is assumed that the animal is not constrained in any other way except the supply of crude protein. It is further assumed that there are no inhibitory nor synergetic tendencies between the different forages used.

The feed input parameters are DM, OMD, GE, ash, CP, CP degradation variables (*a, b, c*, see Table 4.2 for definitions), acid detergent insoluble nitrogen (ADIN). Animal input parameters are initial weight and level of feeding. The dry matter intake without supplementation is set at 2.7% of animal's weight as explained in Section 4.2.4. The dry matter intake of elephant grass supplemented with forage legumes can increase by about 16.7 % as reported in Kariuki et al. (1999); in the current study we used this estimate to raise the intake to 3.2% of body weight. All other parameters are calculated by the model using the respective coefficients as indicated in the equations. The microbial crude protein yield ($y$) is determined by the amount of fermentable metabolisable energy (FME), If effective rumen degradable protein (ERDP) supply is less than (or equal to) ERDP required, then MCP = ERDP else MCP = FME multiplied by $y$.

After part of ME and MP have been used for maintenance, daily gain (DG) is dependent on the balance between Metabolisable Energy for growth (MEg) and Metabolisable Protein for growth (MPg); if potential growth due to metabolisable protein (Gp) is greater than the potential growth due to metabolisable energy (Ge), then MEg is considered limiting and the growth is determined by Ge. Else if potential growth due to metabolisable protein (Gp) is less than potential growth due to metabolisable energy (Ge), then MPg is considered limiting and the growth is determined by Gp. The simulated DG for the two forages is added to get the total DG which is then added to the weight to get a new liveweight (LW), and the process is repeated for the desired number of days. Since forages differ in nitrogen degradability, protein intakes were treated separately rather than summing them.

The simulation model is coded in VENSIM® 5.5 (The Ventana Simulation Environment, Ventana systems, Inc.), based on differential equations with $\Delta t = 1$ day.

### 5.3.1 Evaluation of the simulation model

The performance of the simulation model was evaluated by comparing model predictions to field data reported in Table 4.1, Table 5.1 and Table 5.2 that were never used in the development of the model. The daily gain predicted on the basis of forage composition and animal weight and requirements were compared to the values reported in Kariuki et al. (1999).

## 5.4 Results and discussion

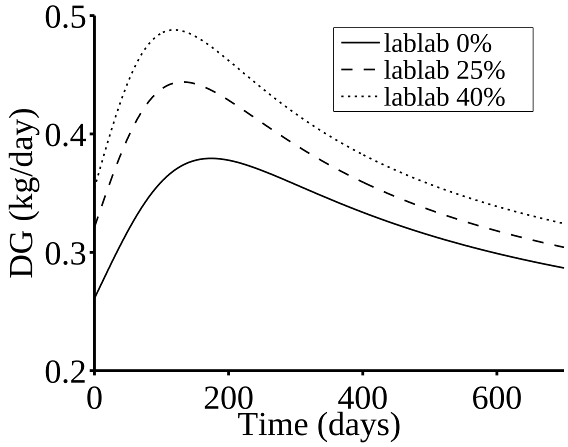
### 5.4.1 Model Calibration and evaluation

Model calibration was based on parameter values in Table 4.1, Table 5.1 and Table 5.2. The simulation model predicted DG of 0.43 kg/day when heifers weighing 181 kg are fed elephant grass supplemented with desmodium for 120 days. This result is similar to field results of 0.42 kg/day reported by Kariuki et al. (1999).

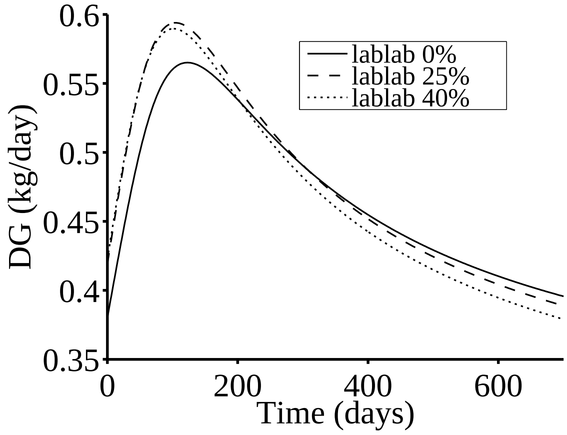
### 5.4.2 Model use

According to Leng (1990), forages are considered as low quality if they have less than 80 g of CP/kgDM and high quality if 100 g of CP/kgDM and above. It is on this basis that CP 75 g/kgDM and 100 g/kgDM were chosen for model use. Figure 5.1 shows the DG of heifers fed elephant grass supplemented with *Lablab purpureus* and *Desmodium spp*. DG improved as the level of the supplement increased (Figure 5.1(a) and Figure 5.1(c)). However, at high levels of napier CP (100 g/kgDM) the benefit of supplementation declined (Figure 5.1(b) and Figure 5.1(d)), whereas at low napier CP (75 g/kgDM) supplementation up to 40% yielded less DG compared to unsupplemented napier at high CP (100 g/kgDM) as shown in Figure 5.2(b). DG was similar for *Lablab purpureus* and *Desmodium spp* (Figure 5.2(a)) supplemented elephant grass.

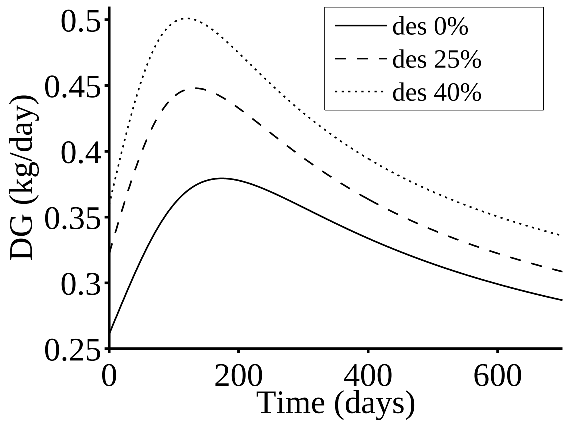
Table 5.3 shows DG and time from weaning to mating weight of 300 kg LW of heifers fed napier grass supplemented with *Lablab purpureus* and *Desmodium spp*. According to the MLD (1991) recommendations in the smallholder dairy farming systems, the weaning weight for dairy heifers



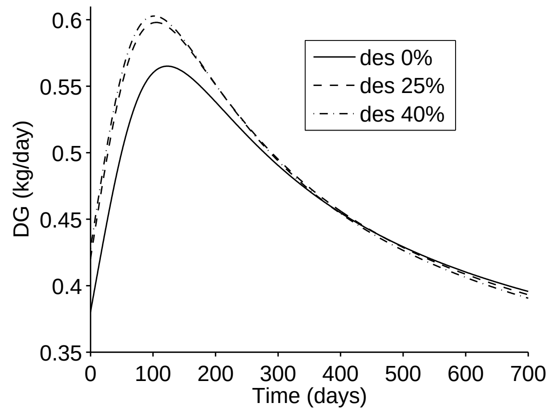

**(a)** Napier at CP 75, with *Lablab purpureus*




**(b)** Napier at CP 100, with *Lablab purpureus*




**(c)** Napier at CP 75, with *Desmodium spp*



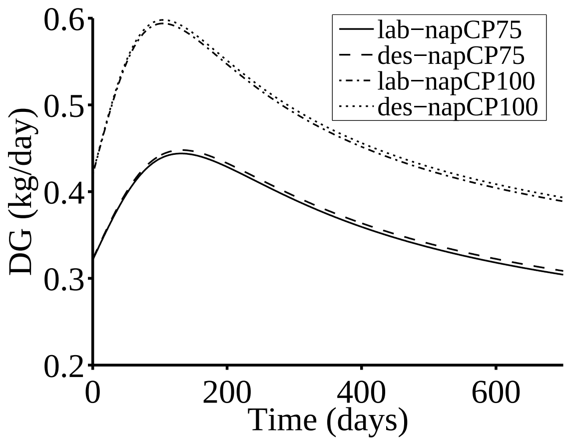

**(d)** Napier at CP 100, with *Desmodium spp*

**Figure 5.1:** Daily gain when elephant grass is supplemented with *Lablab purpureus* and *Desmodium spp* at different levels. 5.1(a): Napier at CP 75 g/kgDM supplemented with *Lablab purpureus* at different levels; 5.1(b): Napier at CP 100 g/kgDM supplemented with *Lablab purpureus* at different levels; 5.1(c): Napier at CP 75 g/kgDM supplemented with *Desmodium spp* at different levels; 5.1(d): Napier at CP 100 g/kgDM supplemented with *Desmodium spp* at different levels.

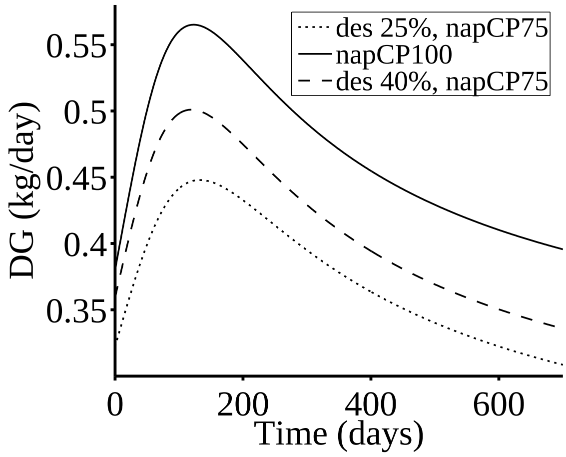
**Table 5.3:** DG and days from weaning to 300 kg LW of heifers fed napier grass supplemented with *Lablab purpureus* and *Desmodium spp*[a]

| | %*Desmodium spp* in diet | | | %*Lablab purpureus* in diet | | |
|---|---|---|---|---|---|---|
| CP[b] | 0 | 25 | 40 | 0 | 25 | 40 |
| 75 | 0.33(691) | 0.39(597) | 0.43(533) | 0.33(691) | 0.38(604) | 0.42(551) |
| 100 | 0.50(461) | 0.52(442) | 0.52(441) | 0.50(461) | 0.52(446) | 0.51(453) |

[a] Values in parentheses are the days
[b] CP in Napier, g/kgDM.




**(a)** Napier at low & high CP supplemented with *Lablab purpureus* and *Desmodium spp* at 25% of diet




**(b)** Napier at CP 75 supplemented with *Desmodium spp* compared to sole napier at CP 100

**Figure 5.2:** Daily gain of heifers when fed elephant at two levels of CP and supplemented with *Lablab purpureus* and *Desmodium spp*. 5.2(a): Napier at CP 75 & 100 g/kgDM, supplemented with *Lablab purpureus* and *Desmodium spp* at 25% of diet; 5.2(b): Napier at CP 75 g/kgDM supplemented with *Desmodium spp* at 25 & 40% of diet, compared to sole napier at CP 100 g/kgDM.

is 70 kg and a target of 300 kg to be attained by 18 months of age for first service. For this target to be met the heifers are assumed to gain at least 0.5 kg/day. From the results of this study (Table 5.3), this target DG is not possible on low quality napier grass. As seen from Table 5.3, low quality elephant grass even when supplemented up to 40% of the diet, it is not possible to attain DG of 0.5 kg/day. However, with high quality elephant grass DG of 0.5 kg/day is possible with or without supplementation (Table 5.3). But higher DG is also seen with high quality elephant grass, but only during the early stages of heifer growth. The lack of improvement in DG as heifers advance in age was also reported by Kariuki et al. (1999) when high quality elephant grass was supplemented with *Desmodium spp*. Therefore, supplementation should be based on quality of elephant grass as well as age/weight of the heifers.

Although the simulation model predictions were similar to observed values (Twinamasiko, 2001; Kariuki et al., 1999), the model has limitations in that only the averages for the observed values were available for model development and evaluation. But to optimize growth there is need to know the growth curve so that the appropriate amount of supplement is given at the right time. Therefore further research on heifer performance in smallholder dairy is needed to accumulate adequate data for developing and evaluating the simulation models of dairy heifer growth. In addition, further research could determine the optimum levels for supplememtation and economic implications.

## 5.5 Conclusion

The simulation model indicates that *Lablab purpureus* and *Desmodium spp* have similar effect on DG. With high CP content in napier grass, effect of supplementation on DG is greatest in early stages of heifer growth and declines thereafter to same levels as sole napier grass. For low CP napier grass, supplementation produced higher DG throughout the entire spectrum of heifer growth. These two forage legumes could therefore improve heifer growth in smallholder dairying, but their inclusion should be based on quality of napier grass as well as age/weight of the heifers.

CHAPTER 6

# Simulating nitrogen excretion, forage growth and animal production

## 6.1 Introduction

Stall-feeding dairy system in Uganda is based on cultivated elephant grass (*Pennisetum purpureum*) as major forage (Muwanga, 1994; Tumutegyereize et al., 1999), partly because of its high biomass yield compared to other grasses (Kabi and Bareeba, 2007). In this dairy system animal manure can be a very good source of nitrogen for forage growth (Rotz et al., 1999). However, the overall farm efficiency of conversion of nitrogen inputs into products is determined by the efficiency of nitrogen cycling through the soil-plant-animal system (Ledgard, 2001). In stall-feeding systems, almost all excreted N could be collected but a proportion of manure N is lost immediately through volatilisation after excretion (Rufino et al., 2006). In addition, manure can lose up to 40% of the N before compositing (Lekasi et al., 2001), and up to 46% of its total N after three months of storage (Thomsen, 2000). On the assumption that all the urinary N is lost, Rufino et al. (2006) estimate a 10% partial cycling efficiency. Therefore, efficient use of manure depends on handling, storage, and method of application (Rufino et al., 2006). For example, the subsurface and surface application of manure gave 77.8% and 26% more dry matter (DM) yield respectively, compared to no manure application (Kabi and Bareeba, 2007).

A number of studies have been carried out on N excretion. They include Zanton and Heinrichs (2008), Nennich et al. (2006), Nennich et al. (2005) Marini and Van Amburgh (2005), Kebreab et al. (2002), and Wilkerson et al. (1997). Models of whole farm N cycling have also been developed (Kohn et al., 1997; Dou et al., 1996). However, these models are not appropriate for stall-feeding systems that depend solely on cultivated *Pennisetum purpureum* where livestock excreta are the only significant N input (Sheldrick et al., 2003). The aim of this study was to predict N excretion and then simulate the effect of excreted N on the forage growth and animal stocking level, by extending the simulation model of heifer growth developed in Chapter 4.

## 6.2 Materials and methods

The AFRC (1993) energy and protein system was used to estimate weight gain and nitrogen output. The procedures, equations and definitions are as given in Chapter 4, Section 4.2, from Subsubsection 4.2.2 to Subsubsection 4.2.7.

### 6.2.1 Forage growth potential and fertilizer value of excreted Nitrogen

Without N fertilizer application, Napier grass yielded 32,400 kg DM ha$^{-1}$ yr$^{-1}$ (Moore and Bushman, 1978), 22,500 kg DM ha$^{-1}$ yr$^{-1}$ (Kabi and Bareeba, 2007), and 18,000 kg DM ha$^{-1}$ yr$^{-1}$ (Binh and Nung, 1995). Based on these findings, the upper limit of elephant grass biomass per hectare was set between 18,000 kg and 22,000 kg DM ha$^{-1}$ yr$^{-1}$. Growth potential of elephant grass as a result of applying excreted N was based on the findings by Binh and Nung (1995) that applying 1 kg N ha$^{-1}$ can yield 34.66 kg DM of elephant grass. Then simulated forage growth potential was established by interfacing the nutrient availability with the forage submodel.

## 6.3 Excreted nitrogen and forage subcomponent

Table 6.1 shows parameters and coefficients used in the simulation model. The nitrogen subcomponent is based on the following calculations:

$$BEN = 0.35 \times W^{0.75} \tag{6.3.1}$$

where $BEN$ is basal endogenous nitrogen. According to Ørskov (1982), $BEN$ is partitioned as 64% fecal and 36% urine, therefore

$$N_u = MP((1-k_n)/6.25) + 0.36 \times BEN \tag{6.3.2}$$

$$\begin{aligned} N_f = {} & (0.25 \times MCP/6.25) + (0.15 \times MTP/6.25) + \\ & ((0.512 \times UDP/6.25) + ADIN) + 0.64 \times BEN \end{aligned} \tag{6.3.3}$$

$$N_t = N_u + N_f \tag{6.3.4}$$

$$N_l = k \times N_t \tag{6.3.5}$$

$$N_n = N_t - N_l \tag{6.3.6}$$

Dynamic equilibrium was assumed for pasture growth and senescence. Forage growth follows the logistic growth function and is estimated as

$$F_a = F_0 \times r_g(1 - F_0/U) - DMI + g \tag{6.3.7}$$

$$IF \quad F_a \geq 0.027 \times W, \quad THEN \quad DMI = 0.027 \times W \times n, \quad ELSE \quad DMI = F_a \tag{6.3.8}$$

$$IF \quad N_n > 0, \quad then \quad g = 18000/365 + (35 \times N_n)/365, \quad ELSE \quad g = 18000/365 \tag{6.3.9}$$

**Table 6.1:** Variables, Parameters and coefficients used in the simulation model

| Variable/Parameter/ Coefficient | Description | Value used[a] |
|---|---|---|
| DMI | Dry matter intake | calculated |
| $F_0$ | Initial forage biomass pool, initialised at 1000 kg | calculated |
| $F_a$ | Available forage biomass, kg/d | calculated |
| g | Forage growth (kg/d) | calculated |
| k | Nitrogen loss coefficient | 0.3 |
| $k_n$ | Efficiency of MP use for animal growth | 0.59 |
| n | Stocking density (number of heifers) | 1 - 6 |
| $N_n$ | Accumulated N excreted less losses | calculated |
| $N_t$ | Total excreted Nitrogen ($N_u$+$N_f$), initialised at 0 | calculated |
| $N_l$ | Nitrogen losses in storage, initialised at 0 | calculated |
| $N_u$ | Urinary nitrogen | calculated |
| $N_f$ | Fecal nitrogen | calculated |
| $r_g$ | Rate of forage increase or decrease | 0.02 |
| U | Maximum ungrazed forage biomass | 18000 |
| W | Weight of the animal, initialised at 70 kg | calculated |

[a] In this column, calculated values are values computed by the model

## 6.4 Results and discussion

### 6.4.1 Nitrogen excretion

Fecal N and urinary N have been found to be closely related to N intake when expressed relative to DMI and $W^{0.75}$ respectively (Zanton and Heinrichs, 2008); results of this study are presented on this basis. Figure 6.1 shows the the partition of excreted N between urine and feces. The percentage N excreted in feces decreased with increasing dietary N, while N excreted in urine increased with increasing N intake. The decrease in fecal N with increasing N intake is due to an increasing dilution of the metabolic fecal N, leading to increased apparent digestibility for N (Marini and Van Amburgh, 2005). The increase in urinary N as N intake increases is due to reduced efficiency of dietary N for growth as requirements are met and the excess N excreted mainly in urine (Nennich et al., 2005). Yet the convention in smallholder is to feed napier grass when young as CP declines with age (Ogwang and Mugerwa, 1976). But feeding forages at an early age leads to loss of nitrogen due to higher degradation in the rumen relative to energy thus resulting in low animal performance (ARC, 1984). At advanced age, forage has relatively higher energy but they are also low in digestibility (Sniffen et al., 1992) leading to low animal performance. A better strategy would be to feed forages when they are young and then tap the excreted nitrogen for recycling.

From this study, relationship between dietary N intake (g/kg of $W^{0.75}$) and urinary N (g/kg of $W^{0.75}$) follow a similar trend to research by Zanton and Heinrichs (2008). Figure 6.2 shows the comparison of results from this study and results of research by Zanton and Heinrichs (2008).

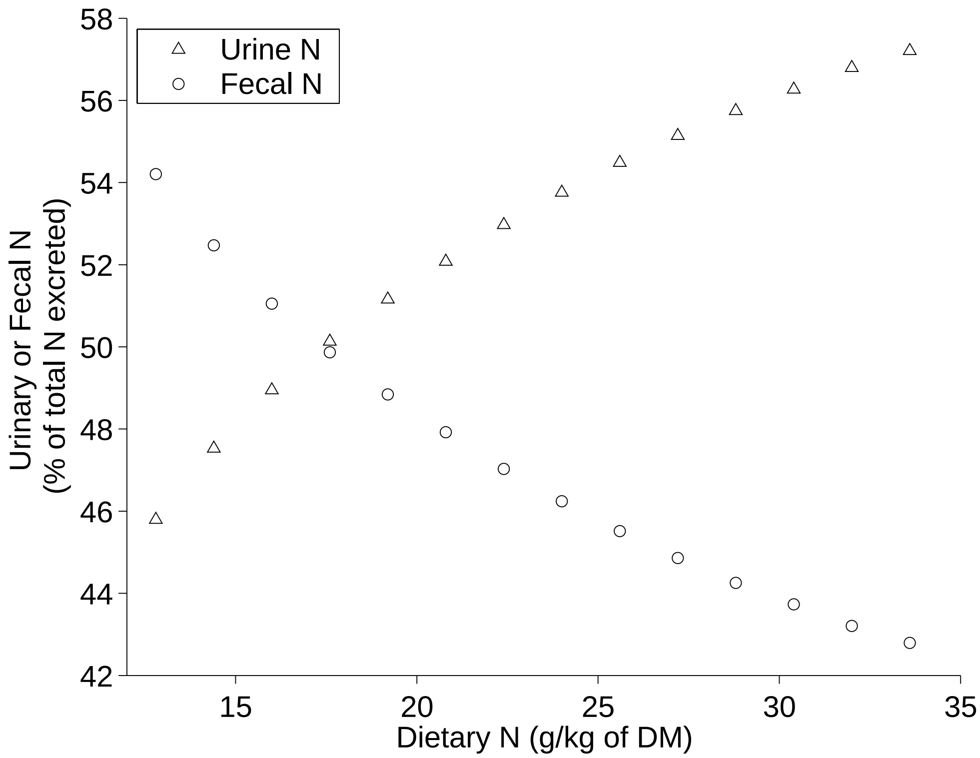



**Figure 6.1:** Route of excreted N in dairy heifers as a function of dietary N

### 6.4.2 Forage growth and animal production

At a stocking level of 3 heifers ha$^{-1}$, without N application the forage biomass accumulates up to 12,000 kg DM ha$^{-1}$ and declines progressively till depletion within two years, whereas with N application the forage biomass accumulates to 17,000 kg DM ha$^{-1}$ and slightly declines to 15,000 kg DM ha$^{-1}$ in the same period (Figure 6.3). With application of excreted N the stocking level can be increased from 3 to 5 heifers ha$^{-1}$ and the system takes the same time to collapse as 3 heifers ha$^{-1}$ with no N application (Figure 6.4), but one more heifer collapses the system within 3 months (Figure 6.5). This increase in stocking level translates to 66.7% increased forage DM yield, that is comparable to 77.8% reported in Kabi and Bareeba (2007) using the subsurface application

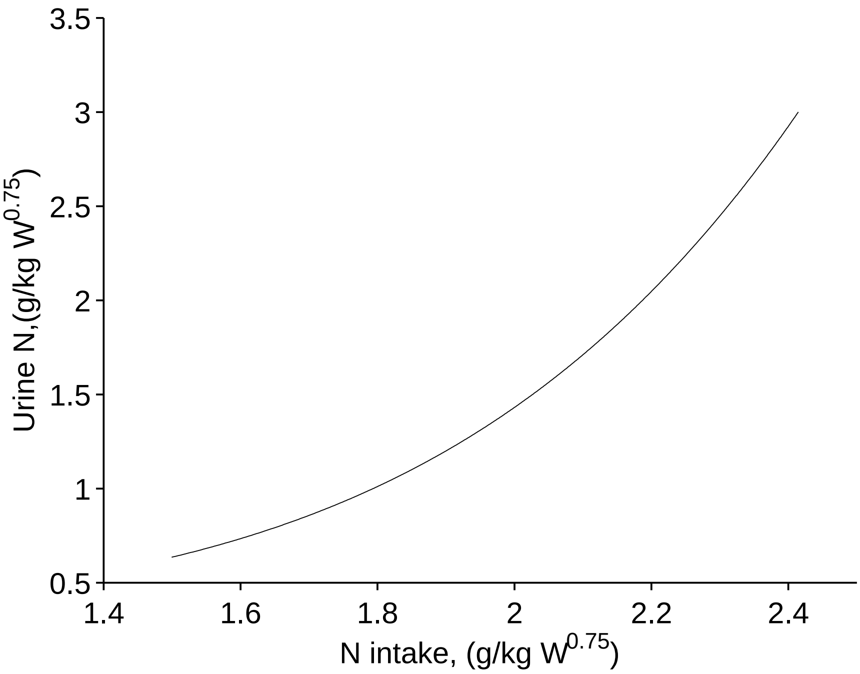



**Figure 6.2:** Relationship between N intake and Urinary N based on metabolic body weight

method. The difference could be explained by the fact that in this simulation model N was the only input whereas in Kabi and Bareeba (2007) the other nutrients in manure could have partly contributed to the observed DM yield. However, During and Weeda (1973) observed that forage biomass increase is mainly due to N although growth responses to phosphorus (P), potassium (K), magnesium (Mg) and calcium (Ca) are expected in poor soils.

Given that efficient use of manure depends on handling, storage, and method of application (Rufino et al., 2006), and the improved DM yield in elephant grass of 77.8% and 26% with subsurface and surface application respectively (Kabi and Bareeba, 2007), it is possible for farmers to improve forage biomass yield and subsequently animal performance by applying manure. Furthermore, nitrogen losses in storage (Lekasi et al., 2001; Thomsen, 2000) and surface application (Sørensen et al., 2003) may be minimised by immediately applying the manure using the subsurface method (Kabi and Bareeba, 2007) and timing the application to synchronise peak mineral N availability and peak plant N demand (Lekasi et al., 2001). These observations were the basis for choosing $k = 0.3$ (Table 6.1).

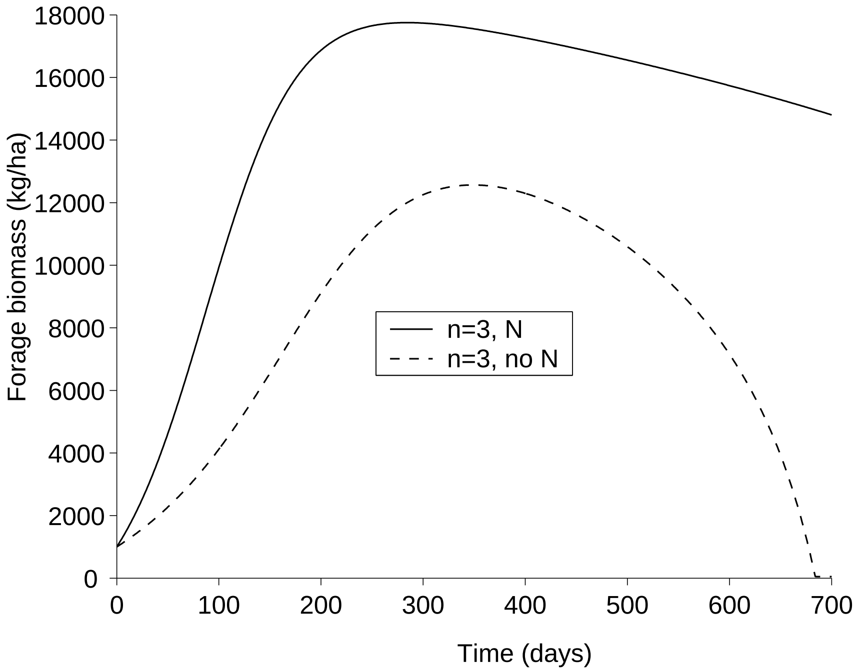



**Figure 6.3:** Forage biomass at fixed stocking level with and without N application

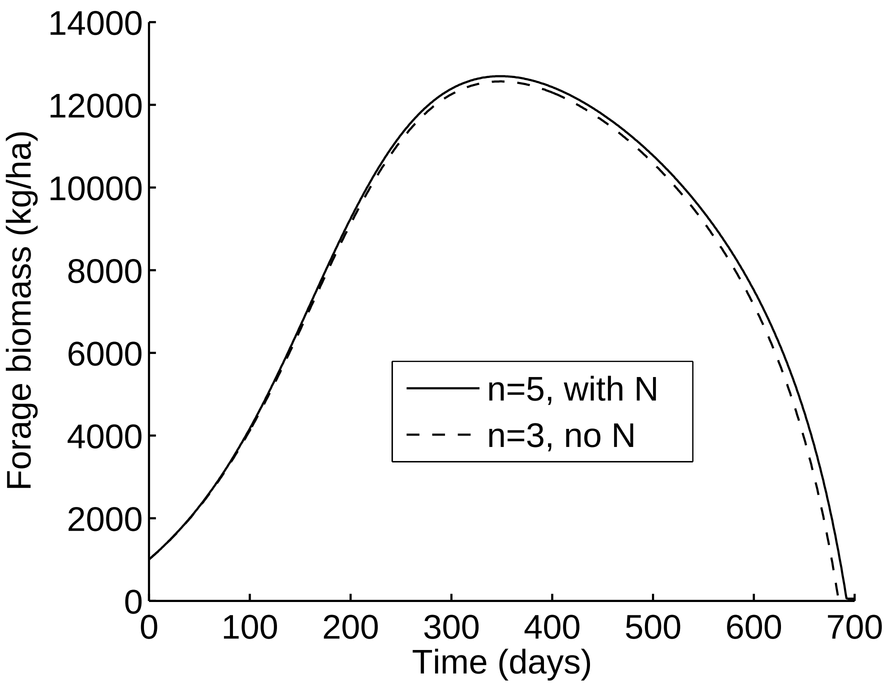



**Figure 6.4:** Forage biomass under different stocking levels and different N regimes

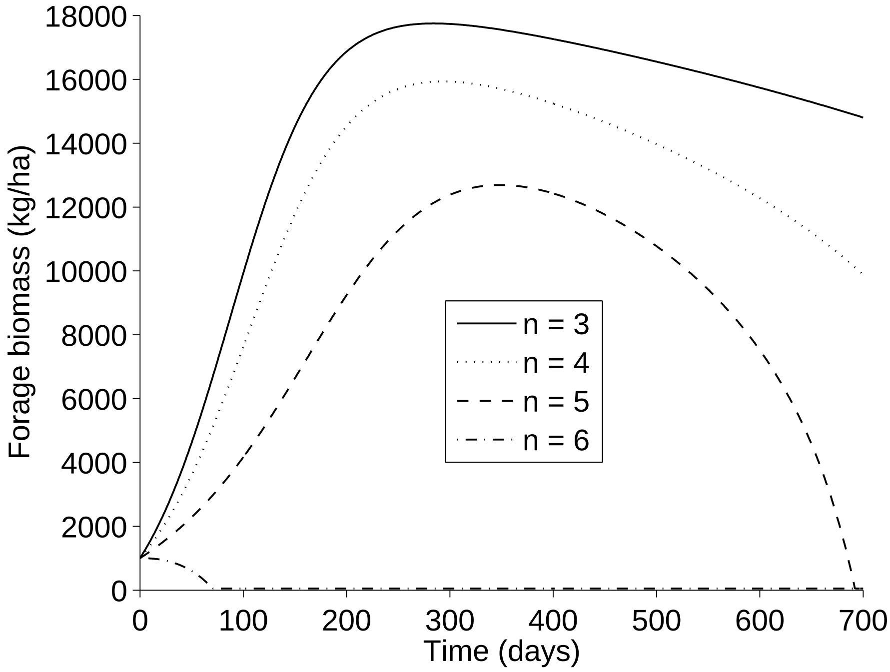



**Figure 6.5:** Forage biomass at different stocking levels with N application

## 6.5 Conclusion

Feeding napier grass when young and thus high in CP, leads to higher urinary nitrogen. By applying excreted nitrogen to napier grass fields, it is possible to improve the forage biomass yield by up to 66.7% and thus increase the stocking level from 3 to 5 heifers ha$^{-1}$.

CHAPTER 7

# Sustainability of livestock-forage system in the cut-and-carry dairying

## 7.1 Introduction

In Chapters 4, 5, 6, and in work done by Tibayungwa et al. (2009) on livestock-forage system the focus was on quantitative analysis. But to answer the question of what type of long-term system dynamics, stability of the system under perturbation, and how the system changes as parameters are varied, the focus should be on bifurcation and stability analysis of the system equilibria (Woodward, 1998). This study focuses on modelling livestock-forage systems for cases where forage biomass is almost always limiting, and therefore necessary to qualitatively analyse the system for dynamical stability over time. Understanding the dynamical behaviour of the the system over time can be crucial to proper planning for the livestock-forage production system.

## 7.2 Methods

The models describe forage accumulation under constant harvesting, and livestock-forage interaction with nutrient cycling. The dynamical systems equations were nondimensionalised, using the procedures outlined in Segel (1972), to reduce the number of parameters to dimensionless groupings that determine the dynamics of the system (Murray, 2002), as this reduction always simplifies the analysis (Strogatz, 1994). Moreover, an additional advantage to nondimensionalising the model is increased efficiency over conventional means of sensitivity analysis (Louie et al., 1998). Stability analysis of steady states was done according to Jordan and Smith (2007). All simulations and bifurcation diagrams were done using XPPAUT (Ermentrout, 2002).

### 7.2.1 Forage growth, intake and stocking density

Forage biomass as a logistic function, with a fixed carrying capacity is given by (Morley, 1968):

$$\frac{dY}{dt} = aY\left(1 - \frac{Y}{K}\right) \tag{7.2.1}$$

where $Y$ (kg ha$^{-1}$) is the forage biomass at any point in time, $a$ is the relative forage growth rate, $K$ is the ceiling yield.

Incorporating a Michaelis-Menten saturation function representing the consumption of the animal gives the following equation

$$\frac{dY}{dt} = aY\left(1 - \frac{Y}{K}\right) - n\frac{rY}{c+Y} \tag{7.2.2}$$

where parameters are defined in Table 7.1.

**Table 7.1:** Variables and Parameters introduced in the one dimensional model, their description, units and dimension

| Variable/ Parameter | Description | Units | Dimension |
|---|---|---|---|
| $Y$ | Forage yield | kg/ha | $ML^{-2}$ |
| $r$ | Daily dry matter intake per animal | kgDM/(animal.day) | $MT^{-1}$ |
| $n$ | Stocking density | animals/ha | $L^{-2}$ |
| $K$ | Maximum forage yield | kg/ha | $ML^{-2}$ |
| $a$ | Relative forage growth | kg/(kg.day) | $T^{-1}$ |
| $c$ | Yield at which intake is half-maximum | kg/ha | $ML^{-2}$ |

By introducing the following dimensionless variables,

$$\tau = at, \quad y = \frac{Y}{K} \tag{7.2.3}$$

substituting and computing the dimensional equation in terms of rescaled time, $\tau = at$, using the chain rule gives

$$\frac{dY}{dt} = \frac{d}{dt}(yK) = \frac{d}{d\tau}(yK)\frac{d\tau}{dt} = \frac{d}{d\tau}(yK)a = aK\frac{dy}{d\tau} \tag{7.2.4}$$

By substituting these expressions into the dimensional equation, and introducing dimensionless parameters $\delta = c/K$ and $\beta = rn/aK$ we get the following nondimensional equation

$$\frac{dy}{d\tau} = y(1-y) - \frac{\beta y}{\delta + y} \tag{7.2.5}$$

### 7.2.2 Forage growth, intake and liveweight gain

In equation (7.2.2) intake is in kg of DM $d^{-1}$, but can also be expressed as kg of DM per liveweight of the animal

$$I = L\frac{fY}{c+Y} \tag{7.2.6}$$

where $I$ is feed intake and $fY/(c+Y)$ is a Michelis-Menten response curve to forage availability; other parameters are in Table 7.2. Substituting the right hand side of equation (7.2.6) into the intake term of equation (7.2.2) yields

$$\frac{dY}{dt} = aY(1-\frac{Y}{K}) - L\frac{fY}{c+Y} \tag{7.2.7}$$

For a growing animal, the forage consumed is used for maintenance and growth and is modelled as

$$I = v\frac{dL}{dt} + mL \tag{7.2.8}$$

Re-arranging and substituting $I$ from equation (7.2.6), gives

$$\frac{dL}{dt} = \frac{1}{v}L\frac{fY}{c+Y} - \frac{m}{v}L \tag{7.2.9}$$

Equations (7.2.7) and (7.2.9) represent a coupled two-dimensional dynamical system for the rates of change of forage yield, $Y$, and animal liveweight, $L$. Model parameters are described in Table 7.2.

$$\frac{dY}{dt} = aY(1-\frac{Y}{K}) - L\frac{fY}{c+Y} \tag{7.2.10a}$$

$$\frac{dL}{dt} = \frac{1}{v}L\frac{fY}{c+Y} - \frac{m}{v}L \tag{7.2.10b}$$

A similar system of equations was proposed by Woodward (1998). However, to ease the difficulty in parameter estimation and analysis, we nondimensionalise the system to reduce the number of parameters and to determine the parameter combinations that control the behaviour of the system (Louie et al., 1998).

**Table 7.2:** Variables and Parameters introduced in the liveweight-forage model, their description, units and dimension.

| Variable/ Parameter | Description | Units | Dimension |
|---|---|---|---|
| $Y$ | Forage yield | kg/ha | $ML^{-2}$ |
| $L$ | Animal biomass (liveweight) per hectare | kg/ha | $ML^{-2}$ |
| $K$ | Maximum forage yield | kg/ha | $ML^{-2}$ |
| $a$ | Relative forage growth | kg/(kg.day) | $T^{-1}$ |
| $f$ | Potential intake per kilogram liveweight | kg/(kg.day) | $T^{-1}$ |
| $c$ | Yield at which intake is half-maximum | kg/ha | $ML^{-2}$ |
| $v$ | Feed conversion efficiency | kg/kg | – |
| $m$ | Feed maintenance requirement | kg/(kg.day) | $T^{-1}$ |

**Table 7.3:** Parameters and parameter combinations used to produce dimensionless variables in the liveweight-forage model

| Variable | Dimension | Parameters used to nondimensionalise | Dimension | Dimensionless variable |
|---|---|---|---|---|
| $Y$ | $ML^{-2}$ | $K$ | $ML^{-2}$ | $y = Y/K$ |
| $L$ | $ML^{-2}$ | $K/v$ | $ML^{-2}$ | $l = Lv/K$ |
| $t$ | $T$ | $a$ | $T^{-1}$ | $\tau = at$ |

From Table 7.3 we see the following dimensionless variables

$$\tau = at, \quad y = Y/K, \quad l = Lv/K \tag{7.2.11}$$

We now solve $y = Y/K$ and $l = Lv/K$ for $Y$ and $L$ to give

$Y = yK$ and $L = lK/v$ that we now substitute into the right-hand of the dimensional equations.

Next we compute the dimensional equations in terms of rescaled time,$\tau = at$, using the chain rule:

$$\frac{dY}{dt} = \frac{d}{dt}(yK) = \frac{d}{d\tau}(yK)\frac{d\tau}{dt} = \frac{d}{d\tau}(yK)\,a = aK\frac{dy}{d\tau} \tag{7.2.12}$$

$$\frac{dL}{dt} = \frac{d}{dt}\left(\frac{lK}{v}\right) = \frac{d}{d\tau}\left(\frac{lK}{v}\right)\frac{d\tau}{dt} = \frac{d}{d\tau}\left(\frac{lK}{v}\right)a = \left(\frac{aK}{v}\right)\frac{dl}{d\tau} \tag{7.2.13}$$

By substituting these expressions, and the following dimensionless groups into dimensional equations,

$$\delta = \frac{c}{K}, \quad \beta = \frac{f}{av}, \quad \alpha = \frac{m}{av} \tag{7.2.14}$$

we arrive at the following nondimensionalised equations

$$\frac{dy}{d\tau} = y(1-y) - \frac{\beta l y}{\delta + y} \tag{7.2.15a}$$

$$\frac{dl}{d\tau} = \frac{\beta l y}{\delta + y} - l\alpha \tag{7.2.15b}$$

By nondimensionalising the system, the number of parameters has reduced from six $(a, K, f, c, m, v)$ to three $(\alpha, \beta, \delta)$. The three nondimensional parameters in terms of the original parameters are listed in Table 7.4.

**Table 7.4:** Nondimensional parameters and values of the parameters used in the simulations of the liveweight-forage system.

| Parameter | Dimension Parameters | Parameter values used in the simulations |
|---|---|---|
| $\alpha$ | $m/av$ | 0.2 |
| $\beta$ | $f/av$ | $0-2$ |
| $\delta$ | $c/K$ | $0-2$ |

### 7.2.3 Forage-animal-nutrient system

The model by Ghosh and Sarkar (1998) on interacting species with nutrient cycling is modified by adding a Michaelis-Menten function that is more appropriate for describing forage yield-soil fertility relationships (Wickham et al., 1997).

$$\frac{dS}{dt} = F - aS - \frac{gSV}{K_s + S} + kcV \tag{7.2.16a}$$

$$\frac{dV}{dt} = \frac{gSV}{K_s + S} - cV - \frac{fNV}{K_1 + V} \tag{7.2.16b}$$

$$\frac{dN}{dt} = \frac{fNV}{K_1 + V} - bN \tag{7.2.16c}$$

where variables and parameters are defined in Table 7.5.

Introducing dimensionless variables (Table 7.6) and dimensionless parameters (Table 7.7) gives the following nondimensional system

$$\frac{dx}{d\tau} = \alpha - x - \frac{xy\beta}{x+\rho} + ky\gamma + qz\eta \tag{7.2.17a}$$

$$\frac{dy}{d\tau} = \frac{xy\beta}{x+\rho} - y\gamma - \frac{yz\delta}{1+y} \tag{7.2.17b}$$

$$\frac{dz}{d\tau} = \frac{yz\delta}{1+y} - z\eta \tag{7.2.17c}$$

**Table 7.5:** Variables and parameters used in the livestock-forage-nutrient system

| Variable/ Parameter | Description | Units | Dimension |
|---|---|---|---|
| $S$ | Amount of nutrient available in soil for forage uptake | kg/ha | $ML^{-2}$ |
| $V$ | Total forage biomass | kg/ha | $ML^{-2}$ |
| $N$ | Animal biomass | kg/ha | $ML^{-2}$ |
| $t$ | Time | days | $T$ |
| $g$ | Relative rate of nutrient uptake per unit biomass of forage | kg/(kg.day) | $T^{-1}$ |
| $F$ | Supply rate of nutrient input to the system | kg/(ha.day) | $ML^{-2}T^{-1}$ |
| $a$ | Rate of loss of nutrient from soil nutrient pool | kg/(kg.day) | $T^{-1}$ |
| $c$ | Rate of loss of forage biomass due to senescence | kg/(kg.day) | $T^{-}1$ |
| $k$ | Fraction of forage biomass that returns to the nutrient pool due to decomposition ($0 < k < 1$) | No Units | – |
| $b$ | Rate of loss of animal biomass due to excretion | kg/(kg.day) | $T^{-1}$ |
| $f$ | Relative intake per unit biomass of herbivore | kg/(kg.day) | $T^{-1}$ |
| $K_1$ | Forage biomass at which animal intake is half -maximum | kg/ha | $ML^{-2}$ |
| $q$ | Fraction of animal biomass that returns to the nutrient pool due to manure excretion ($0 < q < 1$) | No Units | – |
| $K_s$ | Soil nutrient level at which half-maximum intake by forage occurs | kg/ha | $ML^{-2}$ |

**Table 7.6:** Parameters and parameter combinations used to produce dimensionless variables in the livestock-forage-nutrient system

| Variable | Dimension | Parameters used to nondimensionalise | Dimension | Dimensionless variable |
|---|---|---|---|---|
| $S$ | $ML^{-2}$ | $K_1$ | $ML^{-2}$ | $x = S/K_1$ |
| $V$ | $ML^{-2}$ | $K_1$ | $ML^{-2}$ | $y = V/K_1$ |
| $N$ | $ML^{-2}$ | $K_1$ | $ML^{-2}$ | $z = N/K_1$ |
| $t$ | $T$ | $a$ | $T^{-1}$ | $\tau = at$ |

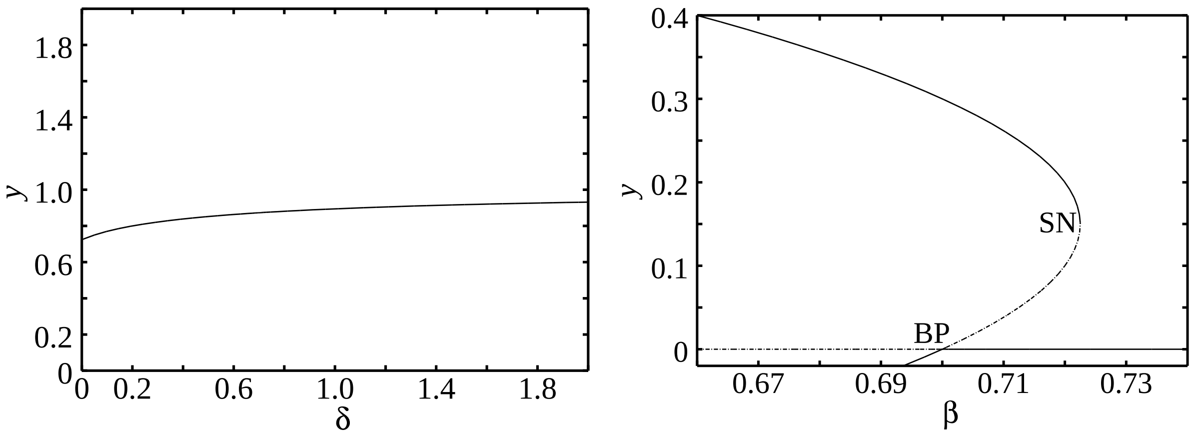
**Table 7.7:** Nondimensional parameters and values of the parameters used in the simulations for the livestock-forage-nutrient system

| Parameter | Dimension Parameters | Parameter values used in the simulations |
|---|---|---|
| $\alpha$ | $F/aK_1$ | $0-2$ |
| $\beta$ | $g/a$ | 1.9 |
| $\delta$ | $f/a$ | 0.2 |
| $\gamma$ | $c/a$ | 0.1 |
| $\eta$ | $b/a$ | 0.1 |
| $\rho$ | $K_s/K_1$ | 0.5 |
| $q$ | $-$ | $0-1$ |
| $k$ | $-$ | 0.5 |

## 7.3 Results and discussion

### 7.3.1 Forage growth, intake and stocking density

Figure 7.1(b) shows the bifurcation diagram of system (7.2.5) for parameter $\beta$ (there was lack of sensitivity to parameter $\delta$). A bifurcation diagram is a graph from a series of points generated by a control parameter that is set at a given value and allowing the system to evolve to an equilibrium state, then recording the equilibrium values for the variables; by repeating this process at successive parameter levels, and finally plotting the recorded values the bifurcation diagram is generated. For low values of $\beta$, with initial value of $y > 0$ and up to about 0.7, the system moves towards the high steady state. This is the bifurcation point (BP), where the sudden change in behaviour occurs as a parameter passes through a critical value (Jordan and Smith, 2007), beyond which the system exhibits discontinuous stability up to about 0.72. Beyond this limit point, known as saddle




**(a)** Bifurcation diagram, $\delta$



**(b)** Bifurcation diagram, $\beta$

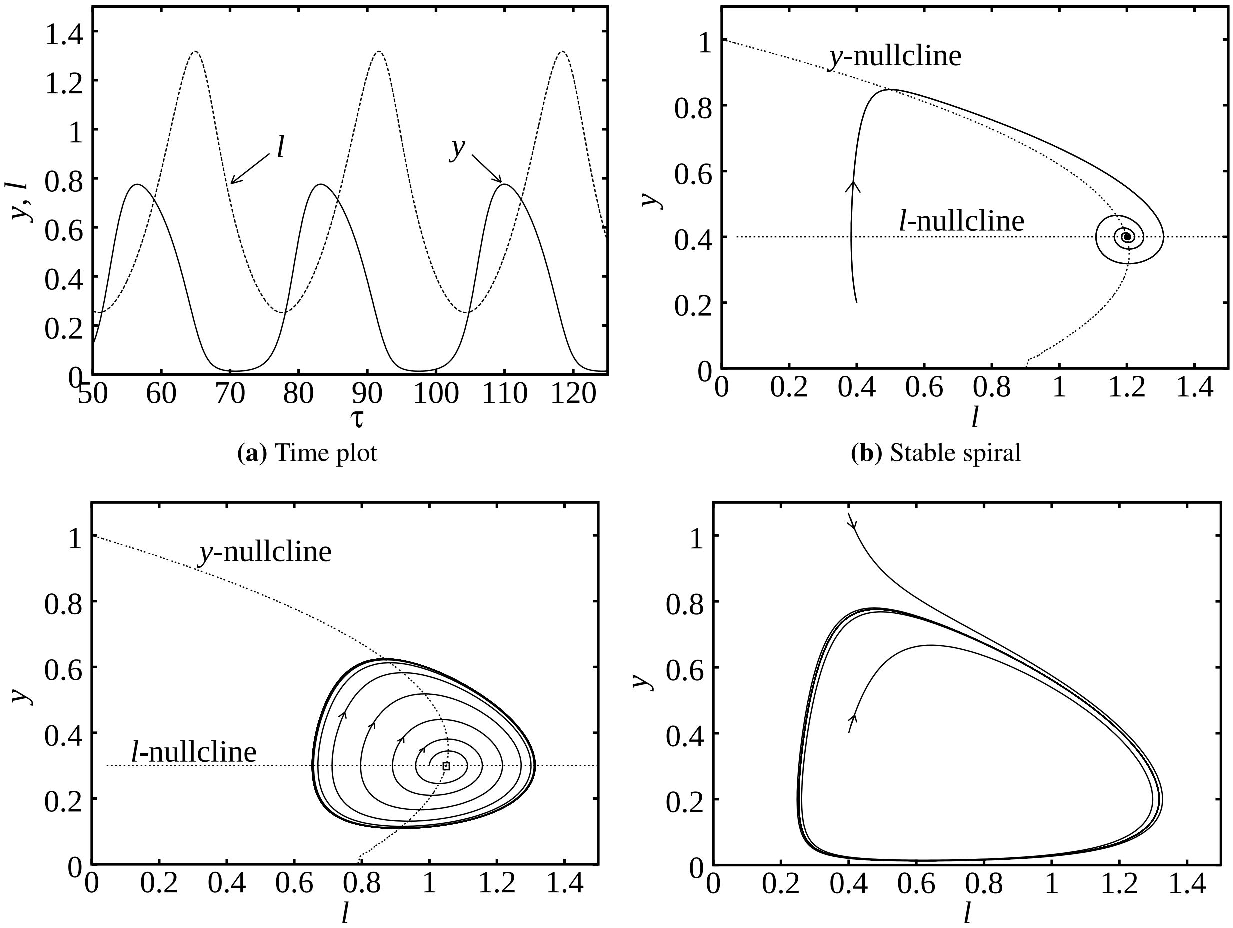
**Figure 7.1:** Bifurcation diagrams for equation (7.2.5). 7.1(a): Bifurcation with $\delta$ as the control parameter, $\beta = 0.2$. Notice lack of sensitivity to $\delta$; 7.1(b): Stable and nonstable states with $\delta = 0.7$. Solid lines show stable steady states, dashed lines show unstable steady states. SN is the sadle node, BP is the bifurcation point (see text for explanation).

node(SN), the system moves towards zero-forage biomass steady state. Farmers practicing zero-grazing tend to maximally utilize their forages, which happens to be the region between BP and SN. The danger of operating in this critical zone (discontinuous stability) is that a small perturbation to the system, for example drought or increased stocking density, can lead to collapse of the system. In addition, if the forage estimates are made without putting into consideration the need to match forage with the growth of the animals, this too leads to collapse of the system unless alternative sources of feed are sought or the animal numbers are reduced.

### 7.3.2 Forage growth, intake and liveweight gain

Figure 7.2 shows the dynamics of Liveweight-forage system (7.2.15). The nullclines represent the system state where neither liveweight nor forage biomass is changing. The horizontal nullcline indicates that the forage available is just enough for feeding the animal at maintenance level, and the intersection point for the two nullclines is the equilibrium point for the system. Stability of the equilibrium point is determined by the direction in which the nearby trajectories evolve; stable equilibrium attracts nearby trajectories whereas unstable equilibrium repels nearby trajectories. Thus, the equilibrium in Figure 7.2(b) is stable and that in Figure 7.2(c) is unstable. However, the stability of the equilibrium or steady state depends on the parameter values, for example, $\beta$ at 0.35

and 0.40 gives results shown in Figure 7.2(b) and Figure 7.2(c) respectively.




**(a)** Time plot **(b)** Stable spiral

**(c)** Unstable spiral **(d)** Stable limit cycle

**Figure 7.2:** Time plot and phase portrait diagrams for livestock-forage model. 7.2(a): Time plot showing the oscillatory behaviour of the system when the steady state is a stable limit cycle; 7.2(b): Stable spiral with a trajectory moving to a stable fixed point, $\beta = 0.35, \delta = 0.3, \alpha = 0.2$; 7.2(c): Unstable spiral with trajectories moving away from unstable fixed point to a limit cycle, $\beta = 0.40, \delta = 0.3, \alpha = 0.2$; 7.2(d): Stable limit cycle with trajectories on either side moving towards the limit cycle for $\alpha = 0.2, \delta = 0.3, \beta = 0.4$.

Tracking the behaviour of the system as the parameters change is done by a two-parameter bifurcation analysis as shown in Figure 7.3(b), where parameter coordinates for $\beta$ and $\delta$ above the curve lead to a fixed point whereas coordinates below the curve lead to a limit cycle.

In Figure 7.3(a) at $\beta << 1$ (intake $<<$ forage growth), $y$ stays at 1.0 up to BP where it drops dramatically to HB (Hopf bifurcation, a point where the equilibrium solutions lose stability). At HB, the equilibrium solutions lose stability and the system evolves to a stable limit cycle surrounding the unstable equilibrium. Explanation for the bifurcation diagrams with reference to $\delta$ is as follows: for Figure 7.3(d) increasing $\delta$ from 1 (likely when carrying capacity has declined or stocking

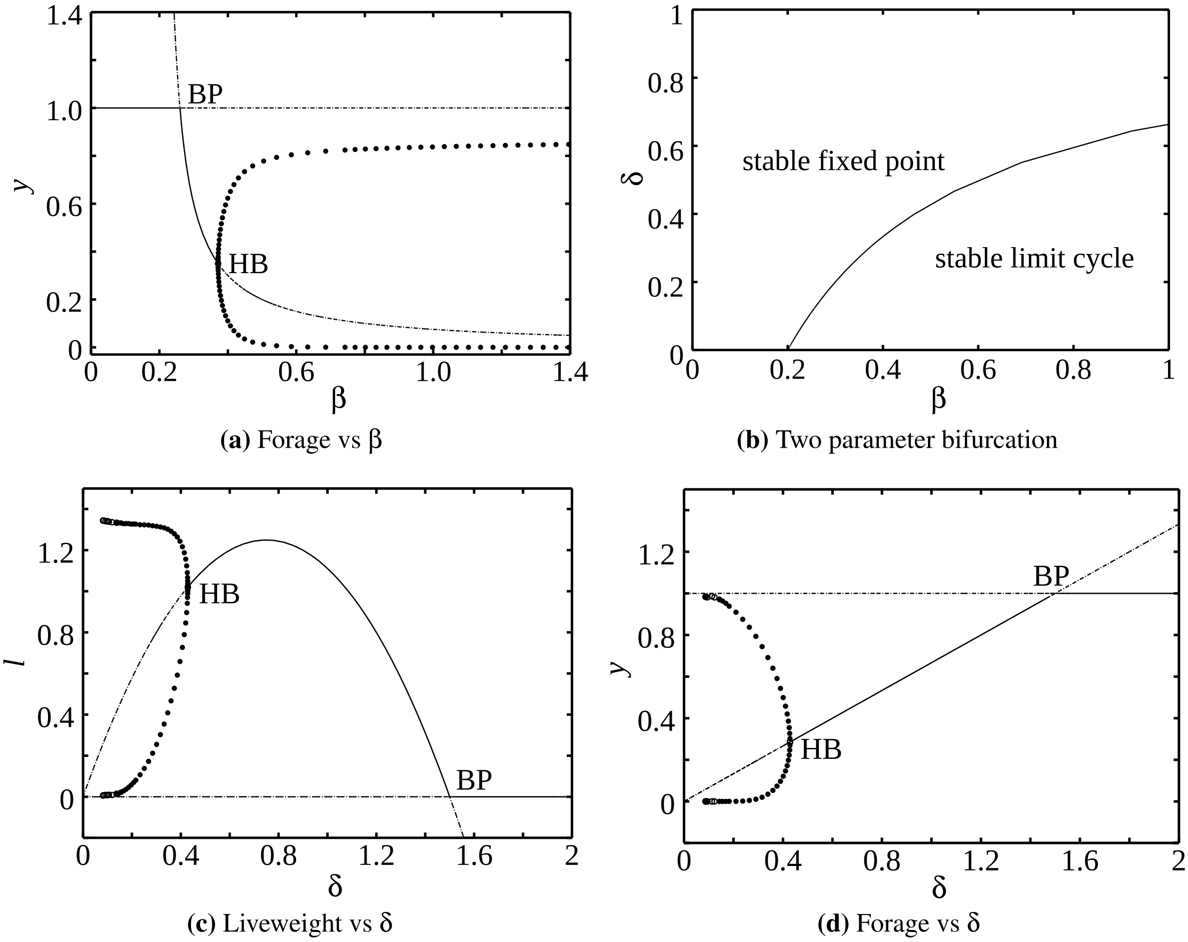
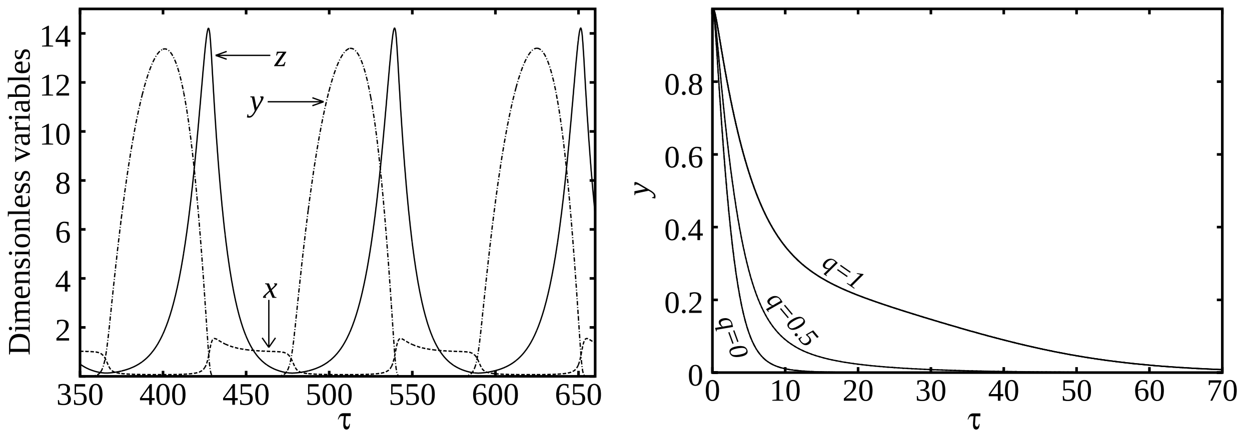



**Figure 7.3:** Bifurcation diagrams for the livestock-forage model. Solid lines show stable steady states, dashed lines show unstable steady states, filled circles show stable limit cycle oscillations, open circles show unstable limit cycle oscillations. 7.3(a): Steady state dimensionless forage biomass with $\beta$ as the control parameter, for $\alpha = 0.2, \delta = 0.3$; 7.3(b): Stability diagram showing the two parameter ($\beta$ and $\delta$), $\alpha = 0.2$; 7.3(c): Steady state dimensionless liveweight with $\delta$ as the bifurcation parameter, for $\alpha = 0.2, \beta = 0.5$; 7.3(d): Steady state dimensionless forage biomass with $\delta$ as the bifurcation parameter, for $\alpha = 0.2, \beta = 0.5$.

density has increased) means there is decreasing forage for the animals up to point (BP) when the forage can no longer support any animals. At this point the animals are either sold or alternative sources of feed sought. But farmers do not wait up to this point, they start looking for alternative feed as early enough usually outsourcing from crop residues or roadside forages. Below $\delta$=1 and up to HB liveweight and forage are in non-zero steady states. At HB the system loses equilibrium stability and evolves to a stable limit cycle surrounding the unstable equilibrium. For values of $\delta$ below HB the system oscillates with increasing amplititudes, as indicated in Figure 7.3(c). This means that at $\delta <<$ HB there is plenty of forage and the farmer can add more animals to the system or conserve forage; if animals are added to the system this reduces the available forage and the system evolves to decreasing oscillations up to HB (Figure 7.3(c)) beyond which the system attains equilibrium.

### 7.3.3 Forage-animal-nutrient system

For the livestock-forage-nutrient I wanted to study the behaviour and stability of the system with or without application of commercial nutrient or excreted nutrient. Therefore, the control parameters




**(a)** Time plot

**(b)** System without fertilizer but with manure

**Figure 7.4:** Time plot and and excreted manure at different levels for the livestock-forage-nutrient system. 7.4(a): Time plot, $\alpha = 1, \beta = 1.9, k = 0.5, \gamma = 0.1, \eta = 0.1$, $\rho = 0.5$, $\delta = 0.2, q = 0.5$; 7.4(b): Nutrient at three levels of $q$, other parameters $\alpha = 0$, $\beta = 1.9$, $k = 0.5, \gamma = 0.1, \eta = 0.1, \rho = 0.5, \delta = 0.2$.

considered are $\alpha$ and $q$. It is assumed that the nutrient referred to here, is essential to the growth of forage and without it no forage growth can occur. Figure 7.4(b) at $q = 0$ (no excreted nutrient added), the system collapses after 10 time-steps ($\tau = 10$), whereas at $q$ = 50% the system takes 30 time-steps (3 times longer to collapse). This clearly indicates the importance of adding excreted nutrient to the forage production. Curve $q = 1$ is an ideal situation where all the excreted nutrient is applied to the production of forage (improbable, but just for comparison purposes). Figure 7.5(a) and Figure 7.5(b) show the different behaviour of the livestock-forage-nutrient system depending on initial conditions and parameter values. However, at the parameters indicated for Figure 7.5(c)

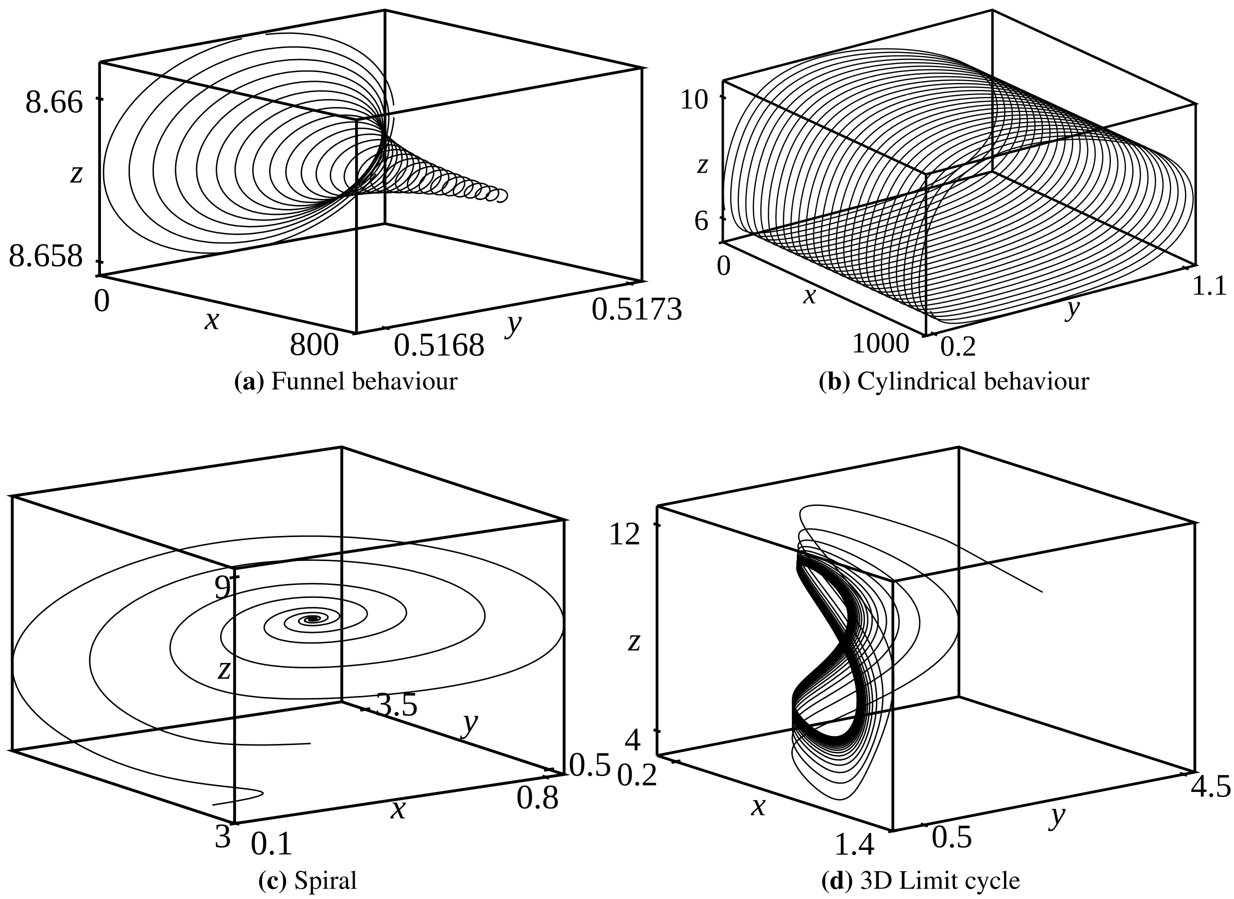
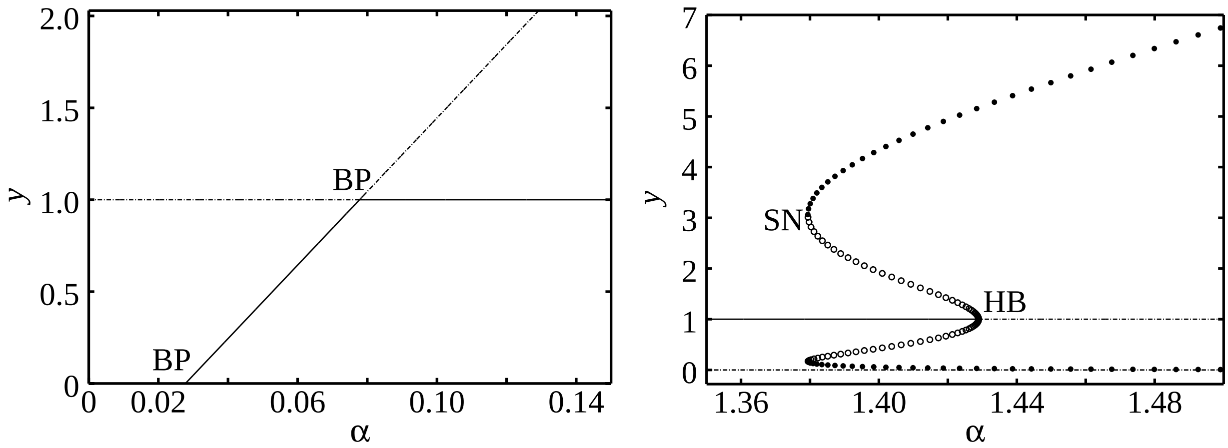



**Figure 7.5:** Livestock-forage-nutrient dynamics. 7.5(a): Funnel spiral behaviour; 7.5(b): Cylindrical spiral dynamics; 7.5(c): Spiral dynamics, $\alpha = 1, \beta = 1.9, k = 0.5, \gamma = 0.1, \eta = 0.1, \rho = 0.5, \delta = 0.2, q = 0.2$; 7.5(d): Limit cycle dynamics, $\alpha = 1, \beta = 1.9, k = 0.5, \gamma = 0.1, \eta = 0.1, \rho = 0.5, \delta = 0.2, q = 0.5$.

and Figure 7.5(d) the system evolves to a stable fixed point and a stable limit cycle respectively. Here the interest was to study the effect of the external nutrient input to the system, and the results are summarised in the bifurcation diagrams (see Figure 7.6(a) & 7.6(b)). At very low levels of $\alpha$ ($\alpha << 1$) and no application of excreted nutrient, $y$ is at the zero-steady state. As $\alpha$, which is a measure of nutrient supply to the soil in a relation to nutrient loss from the soil (see Tables 7.5 & 7.7), increases to the left-most BP, the system moves off the zero-steady state up to BP at $y = 1.0$




**(a)** Forage vs $\alpha << 1$

**(b)** Forage vs $\alpha$

**Figure 7.6:** Bifurcation diagrams for the livestock-forage-nutrient system. Solid lines show stable steady states, dashed lines show unstable steady states, filled circles show stable limit cycle oscillations, open circles show unstable limit cycle oscillations. 7.6(a): Dimensionless forage at $\alpha << 1, \beta = 1.9, k = 0.5, \gamma = 0.1, \eta = 0.1, \rho = 0.5, \delta = 0.2, q = 0$; 7.6(b): Dimensionless forage with $\alpha$ as the control parameter, $\beta = 1.9, k = 0.5, \gamma = 0.1, \eta = 0.1, \rho = 0.5, \delta = 0.2, q = 0$.

(Figure 7.6(a)) where it stays for all the values of $\alpha$ up to HB shown in Figure 7.6(b)).

The bifurcation diagram in Figure 7.6(b) is a continuation of Figure 7.6(a) and is explained as follows. For values of $\alpha$ in the range $SN < \alpha < HB$ the system exhibits two different stable states (solid line and the outer limit cycle with filled circles. The system, within this same range of $\alpha$ values exhibits unstable limit cycle (open circles). This means that with $\alpha$ in the range $SN < \alpha < HB$, and $y$ inside the upper and lower bounds of amplitudes of the unstable limit cycle, the system will evolve towards the stable state indicated by the solid line. But with $y$ outside the bounds of the unstable limit cycle, the system evolves to the outer stable limit cycle. Therefore, starting at HB and increasing $\alpha$ switches the system to the outer limit cycle. However, starting from $\alpha > HB$ and decreasing $\alpha$ to HB, does not bring back the system to the steady state of the solid line. Instead the system continues along the amplitudes of the outer limit cycle up to SN. This lack of reversibility as a bifurcation parameter is varied is called hysteresis (Strogatz, 1994) and has great implications for livestock-forage-nutrient system and is explained as follows.

For $SN < \alpha < HB$ and $y = 1$ the system is stable to small perturbations, for example, if dimensionless forage biomass is changed (but not beyond the unstable limit cycle) due to change in dimensionless animal biomass, the system will evolve back to the fixed point $y = 1$. But if the change is past the unstable limit cycle the system jumps to the outer stable limit cycle. But on this limit cycle the lower dimensionless forage biomass tends to zero-state; and from a management point of view the stable state at $y = 1$ may be more desirable. However, even at $y = 1$ steady state, if $\alpha$ increases beyond $HB$, the only stable state is the outer stable limit cycle. From the definition of $\alpha$ (see Table 7.7), this can happen when there is increased efficiency in retaining external nutrient supply to the system within the forage root domain of nutrient uptake. This increased efficiency can be due to better method of nutrient application, for example, subsurface nutrient application is known to be more efficient than surface application (Kabi and Bareeba, 2007) for the case of Nitrogen. The implication of having the system on the outer limit cycle with $\alpha > HB$ is that the dimensionless animal biomass must change with available dimensionless forage biomass; but this may not be desirable or biologically feasible. For example, it may mean reducing the animal stocking level, outsourcing extra feeds, or allowing the animals to lose weight. If these operations are not the intent of the farmer, then the fixed stable state of $SN < \alpha < HB$ may be an attractive management strategy. However, once the system is in a state where $\alpha > HB$, taking it back to $y = 1$ in the region $SN < \alpha < HB$ means the system first goes back to where $\alpha = SN$ (along the stable outer limit cycle) before it can settle on the $y = 1$ steady state. Since $\alpha$ is a measure of efficiency for retaining external nutrient supply to the system, the desirable level of $\alpha$ is not $SN$ but $HB$. In other words, if the aim of the farmer is to maintain the system with $SN < \alpha < HB$ and $y = 1$, then $\alpha = HB$ is the upper limit of efficiency.

## 7.4 Conclusion

This study has shown the importance of evaluating farmers' forage resources before acquisition of animals since initial conditions influence the stability and sustainability of the system. The study has also shown critical points in the system where management intervention is highly effective depending on the goals of the farmer. Furthermore, not all parameters show sensitivity to the system, and the parameters that show sensitivity have specific parameter space over which they exhibit different sensitivities; this is important in designing experiments and making management decisions. Finally, by organising parameters into dimensionless groups, it is possible to more readily compare relative effects of biological processes.

CHAPTER 8

# General discussion, conclusion and recommendations

## 8.1 Discussion

This research is in two approaches: the systems dynamics and the dynamical systems approach. The systems dynamics approach looks at the growth of dairy heifers fed on napier grass alone, and with legume supplementation. This approach also looks at nitrogen excretion and then using the excreted nitrogen as fertilizer for the growth of napier grass, and the increase in heifer stocking level as a result of the additional forage biomass. In the dynamical systems approach, forage growth, animal intake and stocking density are formulated as a one dimensional system, whereas forage growth, intake and liveweight are formulated as a two dimensional system; and finally, forage growth, animal growth, nutrient excretion and recycling are formulated as a three dimensional system. In all the three dynamical systems models, dimensional analysis is performed to reduce the number of parameters in order to simplify the analysis.

### 8.1.1 Systems dynamics

The weight gain in heifers when fed on napier grass as sole feed increase with increase in forage CP, and there is loss of weight when forage CP falls below heifer maintenance requirement. It was established that when the forage CP falls below 50 g/kgDM, heifer maintenance requirements can no longer be met and the heifers start to lose weight. Since napier grass CP declines with age, it would appear desirable to feed napier when young and thus high in CP. It was established that when forage CP exceed 110 g/kgDM, ME becomes limiting implying that there is need for increasing ME through supplementation. Yet it is when forage CP is above 110 g/kgDM that the requirements for rumen degradable protein would be met if the heifers are to gain at least 0.5 kg day$^{-1}$. The implication is that ME supplementation is desirable for napier grass above CP 110 g/kgDM if the CP is to be efficiently utilised.

This study shows that DG of heifers fed napier grass supplemented with *Lablab purpureus* and *Desmodium spp* improves as the level of the supplement increases. However, at high levels of Napier CP (100 g/kgDM) the benefit of supplementation declines, whereas at low napier CP (75 g/kgDM) supplementation even up to 40% yields less DG compared to unsupplemented napier at high CP (100 g/kgDM). Low quality napier grass even when supplemented up to 40% of the diet, it is not possible to attain the recommended DG of 0.5 kg day$^{-1}$. However, with high quality napier grass DG of 0.5 kg day$^{-1}$ is possible even without supplementation. The benefit of supplementing napier grass with forage legumes is more pronounced when the nutritive value of napier grass is poor; at higher levels of Napier CP higher DG is achieved only during the early stages of heifer growth. This study further indicate that DG as a result of supplementation is similar for both *Lablab purpureus* and *Desmodium spp*, therefore deciding which of the two legumes to use will depend not on their performance in terms of animal performance but on other factors like biomass production, resilience to soil moisture constraint, and cost of production.

Extension of the heifer growth model to incorporate N excretion and cycling shows that the percentage N excreted in feces decreases with increasing dietary N, while percentage of N excreted in urine increases with increasing N intake. Yet the convention in smallholder is to feed Napier grass when young as CP declines with age. But feeding forages at an early age leads to loss of nitrogen due to higher degradation in the rumen relative to energy thus resulting in low animal performance. At advanced age, forage has relatively higher energy but they are also low in digestibility leading to low animal performance. A better strategy would be to feed forages when they are young and then tap the excreted nitrogen for recycling. The developed model was further used to simulate the application of nitrogen on forage biomass production and the heifers the additional forage biomass can support. With application of excreted N the stocking level increases from 3 to 5 heifers ha$^{-1}$ and the system takes the same time to collapse as 3 heifers ha$^{-1}$ with no N application.

### 8.1.2 Dynamical systems

To get insight into long-term system dynamics, dynamical systems of forage biomass accumulation under continuous harvesting with and without nutrient cycling are formulated and studied. For one dimensional dynamical system with $\beta$ being a measure of forage intake relative to forage growth, there is bifurcation at $\beta = 0.70$ whereas at $0.70 < \beta < 0.72$ the system exhibits discontinuous stability, and at $\beta > 0.72$ the system collapses. Farmers practicing stall-feeding tend to maximally utilize their forages, which happens to be the region $0.70 < \beta < 0.72$ characterised by discontinuous stability. In this region, a small perturbation to the system, for example drought or increased stocking density, leads to collapse of the system. In addition, if the forage estimates are made without putting into consideration the need to match forage with the growth of the animals, this too leads to collapse of the system unless alternative sources of feed are sought or the animal numbers are reduced.

For a two dimensional dynamical system, there is bifurcation at $\beta = 0.26$, stable equilibrium at $0.26 < \beta < 0.37$ and unstable equilibrium at $\beta > 0.37$. Increasing $\delta$ from 1 leads to decreasing forage for the animals up to a bifurcation point (BP) when the forage can no longer support any animals. Farmers that have no alternative sources of feed will have to sell off the animals. Below $\delta$=1 liveweight and forage stay in non-zero steady states up to a point (HB) where stability is lost. It is at this point HB that the system evolves to a stable limit cycle surrounding the unstable equilibrium. For values of $\delta$ below HB the system oscillates with increasing amplititudes. This means that at $\delta <<$ HB there is plenty of forage and the farmer can add more animals to the system or conserve forage; if animals are added to the system this reduces the available forage and the system evolves to decreasing oscillations up to HB beyond which the system attains equilibrium again.

For the three dimensional dynamical system where $\alpha$ is a measure of soil nutrient replenishment, at $1.38 < \alpha < 1.43$ the system exhibits two different stable states (a fixed point and a limit cycle) and one unstable state (limit cycle), and at $\alpha > 1.43$ there is only one stable state (limit cycle). For $y = 1$ and $1.38 < \alpha < 1.43$, there is local stability but no global stability. For $SN < \alpha < HB$ and $y = 1$ the system is stable to small perturbations, and will evolve back to the fixed point

$y = 1$. If there is increased efficiency in retaining external nutrient supply to the system within the forage root domain of nutrient uptake, for example due to better method of nutrient application, and the system is perturbed past the unstable limit cycle the system jumps to the outer stable limit cycle. However, once the system is in a state where $\alpha > HB$, taking it back to $y = 1$ in the region $SN < \alpha < HB$ means the system first goes back to where $\alpha = SN$ along the stable outer limit cycle (the system exhibits hysteresis) before it can settle on the $y = 1$ steady state. This may mean reducing the animal stocking level, outsourcing extra feeds, or allowing the animals to lose weight. But these operations may not be desirable or biologically feasible, and if the aim of the farmer is to maintain the system with $SN < \alpha < HB$ and $y = 1$, then $\alpha = HB$ is the upper limit of efficiency.

## 8.2 Conclusion

The recommended DG of heifers in smallholder system of 0.5 kg day$^{-1}$ can be attained without supplementation when napier grass is 6 to 8 weeks of age. But when CP exceeds 110 g/kgDM ME is limiting and there is need for ME supplementation if CP is to be efficiently utilised.

Supplementing napier grass with forage legumes improves DG only when the nutritive value of napier grass is poor. At napier CP $\geq$ 100 g/kgDM the benefit of supplementation declines, whereas at napier CP $\leq$ 75 g/kgDM supplementation even up to 40% yields less DG compared to unsupplemented napier at CP $\geq$ 100 g/kgDM. Low quality napier grass even when supplemented with *Lablab purpureus* or *Desmodium spp* up to 40% of the diet, it is not possible to attain the recommended DG of 0.5 kg day$^{-1}$. It is further concluded that DG as a result of supplementation is similar for both *Lablab purpureus* and *Desmodium spp*, therefore deciding which of the two legumes to use will depend not on their performance in terms of animal weight gain but on other factors like biomass production, resilience to soil moisture constraint, and cost of production.

The application of excreted N for napier grass growth increases the stocking level from 3 to 5 heifers ha$^{-1}$ and the system takes the same time to collapse as 3 heifers ha$^{-1}$ with no N application.

Through bifurcation analysis, critical points of the system can be identified for timely intervention. Further, by using dimensional analysis, it possible to more readily compare relative effects of biological processes.

The systems dynamics model can be extended to handle any number of feedstuffs provided input parameters are available. The dynamical systems models are useful to understand the long-term dynamics of livestock-forage system with and without nutrient cycling. These models are useful research and educational tools for evaluating long-term performance and sustainability of small-holder dairy systems.

## 8.3 Recommendations

Napier grass should be fed to heifers when it is high in nutritive value, preferably from 6 weeks to 8 weeks of age. Lablab and desmodium should be used to supplement napier grass but their inclusion should be based on quality of elephant grass as well as age/weight of the heifers. Animal manure should be applied to the fields to increase biomass production of napier grass.

Since long-term stability of the livestock-forage system primarily depends on the stocking levels and initial forage biomass, planning should be done to match forage with the growth of the animals; otherwise the system collapses unless alternative sources of feed are sought or animal numbers reduced.

## 8.4 Future work

The systems dynamics model can be developed further to include the substitution effect, and synergy between different feedstuffs. The model can be extended to include the gestation phase in heifers, and include cows at different physiological stages to fully represent the production cycle as experienced on-farm. The model can further be extended to include inter-cropping napier with forage legumes.

For the dynamical systems model on forage-livestock-nutrient further work can be to determine whether the model exhibits chaotic behavior and the associated parameter values, and the implication for smallholder stall-feeding dairy systems.

# References


AFRC (1993). *Energy and Protein Requirements of Ruminants*. Agricultural and Food Research Council. CAB International, Wallingford, UK.

Agbenin, J. and Goladi, J. (1998). Long-term soil fertility trend in the savanna as influenced by farmyard manure and inorganic fertiliser. In Renard, G., Neef, A., Becker, K., and von Oppen, M., editors, *Soil Fertility Management in West African Land Use Systems*, pages 21–29. Weikersheim, Germany, Margraf Verlag.

Anindo, D. O. and Potter, H. L. (1994). Seasonal variation in productivity and nutritive value of Napier grass at Muguga, Kenya. *E. African Agriculture and Forestry Journal*, 59:177–185.

Anindo, D, O. and Potter, H. L. (1986). Milk production from napier grass (*Pennisetum purpureum*) in zero grazing feeding system. *E. Afr. Agric. For. J.*, 52:106–111.

ARC (1984). *The nutrient requirement of ruminant livestock, Supplement No. 1.* CAB, Slough, England.

Aregheore, E. M., steglar, T. A., and Ng'ambi, J. W. (2006). Nutrient characterisation and *in vitro* digestibility of grass and legume/browse species - based diets for beef cattle in vanuatu. *The South Pacific Journal of Natural Science*, 24(1):20–27.

Bach, A., Calsamiglia, S., and Stern, M. D. (2005). Nitrogen metabolism in the rumen. *J. Dairy Sci.*, 88:(E. Suppl.):E9–E21.

Baldwin, R. L. and Miller, P. S. (1989). Modelling energy metabolism. In *Energy metabolism of farm animals.* Pudoc, Wageningen, The Netherlands. pp. 239-242.

Baldwin, R. L., Thornley, J. H. M., and Beever, D. E. (1987). Metabolism of the lactating cow. II. Digestive elements of a mechanistic model. *Journal of Dairy Research*, 54:107–131.

Baloyi, J. J., Ngongoni, N. T., and Hamudikuwanda, H. (2008). Chemical composition and ruminal degradability of cowpea and silverleaf desmodium forage legumes harvested at different stages of maturity. *Tropical and Subtropical Agroecosystems*, 8:81–91.

Barrett, C. (1999). Food security and food assistance programs. In Gardner, B. L. and Rausser, G. C., editors, *Handbook of Agricultural Economics*. Elsevier Science, Amsterdam.

Binh, L. H. and Nung, H. V. (1995). Enhancing sustainable livestock-crop production in smallholder-farming systems. In *Proceedings of the fourth meeting of Regional Working Group on Grazing and Feed Resources of Southeast Asia, 20-24 March*, page 251, Nha Trang, Vietnam.

Blomquist, N. (2005). How much will my cow eat? - Frequently asked questions. Technical report, Alberta Ag-Centre, Alberta Agriculture, Food and Rural Development, Government of Alberta.

Boonman, J. G. (1993). *East African grasses and Fodder, Their Ecology and Husbandry*. Kluwer Academic Publishers.

Brock, F. M., Forsberg, C. W., and Buchanan-Smith, J. G. (1982). Proteolytic activity of rumen microorganisms and effects of proteinase inhibitors. *Appl. Environ.Microbiol.*, 44:561–569.

Brown, L., Scholefield, D., Jewkes, E., Lockyer, D., and del Prado, A. (2005). NGAUGE: A decision support system to optimise n fertilisation of british grassland for economic and environmental goals. *Agriculture, Ecosystems & Environment*, 109(1-2):20 – 39.

de Wit, C. T. (1992). Resource use efficiency in agriculture. *Agricultural Systems*, 40:125–151.

Delgado, C., Rosegrant, M., Steinfeld, H., Ehui, S., and Courbois, C. (1999). Livestock to 2020. the next food revolution. food, agriculture, and the environment discussion paper 28. Technical report, IFPRI/FAO/ILRI.

Diaz-Solis, H., Kothmann, M. M., Grant, W. E., and De Luna-Villarreal, R. (2006). Application of a simple ecological sustainability simulator (SESS) as a management tool in the semi-arid rangelands of northeastern Mexico. *Agricultural Systems*, 88(2-3):514–527.

Dou, Z., Kohn, R. A., Ferguson, J. D., Boston, R. C., and Newbold, J. D. (1996). Managing Nitrogen on Dairy Farms: An Integrated Approach I. Model Description. *J. Dairy Sci.*, 79(11):2071–2080.

During, C. and Weeda, W. C. (1973). Some effects of cattle dung on soil properties, pasture production, and nutrient uptake. I. Dung as a source of phosphorus. *N. Z. J. Agric. Res.*, 16:423–430.

Elbasha, E., Thornton, P., and Tarawali, G. (1999). An Ex-Post Economic Impact Assessment of Planted Forages in West Africa. Technical report, International Livestock Research Institute. Nairobi, Kenya.

Ermentrout, G. B. (2002). *Simulating, Analyzing, and Animating Dynamical Systems: A Guide to XPPAUT for Researchers and Students.* SIAM Books, Philadelphia.

Esilaba, A. O., Byalebeka, J. B., Nakiganda, A., Mubiru, S., Delve, R. J., Ssali, H., and Mbalule, M. (2002). Integrated nutrient management strategies in Eastern Uganda. In *17th WCSS, 14-21 August 2002, Thailand.*

FAO (1998). State of Food and Agriculture. Technical report, FAO.

Fernandes, E. C. M. and Sanchez, P. A. (1990). The role of organic inputs and soil organic matter for nutrient cycling in tropical soils. In *Organic-Matter Management and Tillage in Humid and Subhumid Africa*, pages 169–187. Int. Board Soil Res. Mgmt., Bangkok, Thailand.

Ferraris, R. and Sinclair, D. F. (1980). Factors affecting the growth of *Pennisetum purpureum* in the wet tropics. II. Uninterrupted growth. *Australian Journal of Agricultural Research*, 31:915–925.

France, J., Gill, M., Thornley, J. H. M., and England, P. (1987). A model of nutrient utilization and body composition in beef cattle. *Animal Production*, 44:371–385.

Freer, M., Moore, A. D., and Donnelly, J. R. (1997). GRAZPLAN: decision support systems for Australian grazing enterprises. II The animal biology model for feed intake, production and reproduction and the GrazFeed DSS. *Agricultural Systems*, 54:77–126.

Getachew, G., Makkar, H. P. S., and Becker, K. (2000). Effect of polyethylene glycol on *in vitro* degradability of nitrogen and microbial protein synthesis from tannin-rich browse and herbaceous legumes. *British Journal of Nutrition*, 84:73–83.

Ghosh, D. and Sarkar, A. K. (1998). Stability and oscillations in a resource-based model of two interacting species with nutrient cycling. *Ecological Modelling*, 107(1):25 – 33.

Gitau, G. K., McDermott, J. J., Adams, J. E., Lissemore, K. D., and Waltner-Toews, D. (1994). Factors influencing calf growth and daily weight gain on smallholder dairy farms in Kiambu District, Kenya. *Prev. Vet. Med.*, 21:179–190.

Harris, F. (1995). Nutrient dynamics in the Kano close-settled zone. *ILEIA Newsletter*, pages 16–17.

Hassan, N. I., Abdelaziz, H. M., and El Tabbah, A. E. (1979). Evaluation of some forages introduced to newly reclaimed areas in Egypt. *World Rev. of Animal Production*, XV (2):31–35.

Hassan, N. I., Osman, F. A., and Rammah, A. M. (1983). Morphological characters, chemical composition and in vitro dry matter disappearance of new varieties of napier grass grown in Egypt. *World Rev. of Animal Production*, XIX (4):35–40.

Herrero, M., Dent, J. B., and Fawcett, R. H. (1998). The plant/animal interface in models of grazing systems. In Peart, R. M. and Curry, R. B., editors, *Agricultural Systems Modeling and Simulation*, pages 495–542. Marcel Dekker Publishers, New York, USA.

Hill, J. O., Robertson, M. J., Pengelly, B. C., Whitbread, A. M., and Hall, C. A. (2006). Simulation modelling of lablab (*Lablab purpureus*) pastures in northern Australia. *Australian Journal of Agricultural Research*, 57(4):389–401.

Hoang Fagerström, M. H., Messing, I., and Wen, Z. M. (2003). A participatory approach for integrated conservation planning in a small catchment in Loess Plateau, China: Part I. Approach and Methods. *Catena*, 54:255–269.

Humphreys, L. R. (1994). *Tropical forages: Their role in sustainable agriculture.* Longman, Harlow, UK.

Illius, A. W. and Allen, M. S. (1994). Assessing forage quality using integrated models of intake and digestion in ruminants. In Fahey, G. J., Collins, M., Mertens, D. R., and Moser, L. E., editors, *Forage Quality, Evaluation and Utilization*, pages 869–890. American Society of Agronomy, Madison, USA.

Illius, A. W. and Gordon, I. J. (1991). Prediction of intake and digestion in ruminants by a model of rumen kinetics integrating animal size and plant characteristics. *Journal of Agricultural Science, Cambridge*, 116:145–157.

Jingura, R. M., Sibanda, S., and Hamudikuwanda, H. (2001). Yield and nutritive value of tropical forage legumes grown in semi-arid parts of zimbabwe. *Tropical Grasslands*, 35:168–174.

Jones, P. G. and Thornton, P. K. (2009). Croppers to livestock keepers: livelihood transitions to 2050 in africa due to climate change. *Environmental Science & Policy*, 12(4):427 – 437.

Jordan, D. W. and Smith, P. (2007). *Nonlinear Ordinary Differential Equations*. Oxford University Press Inc., New York, 4th edition.

Kabi, F. and Bareeba, F. B. (2007). Factors influencing adoption of cattle excreta management practices for improved elephant grass (*Pennisetum purpureum*) production by smallholder dairy farmers. *Livestock Research for Rural Development.*, Volume 19, Article No.24.:Retrieved June 11, 2008, from http://www.cipav.org.co/lrrd/lrrd19/2/kabi19024.htm.

Kabi, F., Bareeba, F. B., Havrevoll, O., and Mpofu, I. D. T. (2005). Evaluation of protein degradation characteristics and metabolisable protein of elephant grass (*Pennisetum purpureum*) and locally available protein supplements. *Livestock Production Science*, 95(1-2):143–153.

Kabirizi, J. M. (2006). *Effect of intergrating forage legumes in smallholder dairy farming systems on feed availability and animal performance*. PhD thesis, Makerere University, Kampala, Uganda.

Kariuki, J. N., Gachuiri, C. K., Gitau, G. K., Tamminga, S., van Bruchem, J., Muia, J. M. K., and Irungu, K. R. G. (1998). Effect of feeding napier grass, lucerne and sweet potato vines as sole diets to dairy heifers on nutrient intake, weight gain and rumen degradation. *Livestock Production Science*, 55(1):13–20.

Kariuki, J. N., Gitau, G. K., Gachuiri, C. K., Tamminga, S., and Muia, J. M. K. (1999). Effect of supplementing napier grass with desmodium and lucerne on DM, CP and NDF intake and weight gains in dairy heifers. *Livestock Production Science*, 60(1):81–88.

Kebreab, E., France, J., Mills, J. A. N., Allison, R., and Dijkstra, J. (2002). A dynamic model of N metabolism in the lactating dairy cow and an assessment of impact of N excretion on the environment. *J Anim Sci*, 80(1):248–259.

Kebreab, E., Smith, T., Tanner, J., and Osuji, P. (2005). Review of undernutrition in smallholder ruminant production systems in the tropics. In Ayatunde, A. A., Fernández-Riviera, S., and McCrabb, G., editors, *Coping with feed scarcity in smallholder livestock systems in developing countries.*, pages 3–94. Animal Sciences Group, Wageningen UR, Wageningen, The Netherlands, University of Reading, Reading, UK, ETH (Swiss Federal Institute of Technology), Zurich, Switzerland, and ILRI (International Livestock Research Institute), Nairobi, Kenya. 306 pp.

Kertz, A. F., Barton, B. A., and Reutzel, L. F. (1998). Relative Efficiencies of Wither Height and Body Weight Increase from Birth Until First Calving in Holstein Cattle. *Journal of Dairy Science*, 81(5):1479–1482.

Koenen, E. P. C. and Groen, A. F. (1996). Genetic Analysis of Growth Patterns of Black and White Dairy Heifers. *Journal of Dairy Science*, 79(3):495–501.

Kohn, R. A., Dou, Z., Ferguson, J. D., and Boston, R. C. (1997). A sensitivity analysis of nitrogen losses from dairy farms. *Journal of Environment Management*, 50:417–428.

Ledgard, S. F. (2001). Nitrogen cycling in low input legume-based agriculture, with emphasis on legume/grass pastures. *Plant and Soil*, 228:43–59.

Lekasi, J. K., Tanner, J. C., Kimani, S. K., and Harris, P. J. C. (2001). Managing Manure to Sustain Smallholder Livelihoods in the East African Highlands. Technical report, HDRA, Coventry, UK.

Leng, R. A. (1990). Factors affecting the utilisation of 'poor quality' forages by ruminants particularly under tropical conditions. *Nutr. Res. Rev.*, 3:277–303.

Linga, S. S., Lukefahr, S. D., and Lukefahr, M. J. (2003). Feeding of *Lablab purpureus* forage with molasses blocks or sugar cane stalks to rabbit fryers in subtropical south Texas. *Livestock Production Science*, 80(3):201–209.

Louie, K., Clark, H., and Newton, P. C. D. (1998). Analysis of differential equation models in biology: a case study for clover meristem populations. *New Zealand Journal of Agricultural Research*, 41:567–576.

MAAIF (1996). *Study Report on The Comparative Analysis of Cattle Management systems in Different Areas of Uganda*. Ministry of Agriculture Animal Industry and Fisheries. Entebbe, Uganda.

MAAIF (2004). *Basic Agricultural Statistics 2004*. Agricultural Planning Department. Ministry of Agriculture, Animal Industry and Fisheries. Entebbe, Uganda.

Marini, J. C. and Van Amburgh, M. E. (2005). Partition of nitrogen excretion in urine and the feces of holstein replacement heifers. *J Dairy Sci*, 88(5):1778–1784.

Mbuthia, E. W. and Gachuiri, C. K. (2003). Effect of inclusion of *Mucuna pruriens* and *Dolichos lablab* forage in napier grass silage on silage quality and on voluntary intake and digestibility in sheep. *Tropical and Subtropical Agroecosystems*, 1:123–128.

Melaku, S., Peters, K. J., and Tegegne, A. (2003). In vitro and in situ evaluation of selected multi-purpose trees, wheat bran and *Lablab purpureus* as potential feed supplements to tef (*Eragrostis tef*) straw. *Animal Feed Science and Technology*, 108(1-4):159–179.

Mghen, D. M., Hvelplund, T., and Weisbjerg, M. R. (1996). Rumen degradability of dry matter and protein in tropical grass and legume forages and their protein values expressed in the AAT-PBV protein evaluation system. In Ndikumana, J. and de Leeuw, P., editors, *Sustainable Feed Production and Utilization of Smallholder Livestock Enterprises in Sub-Saharan Africa. Proceedings of the Second African Feed Resources Network (AFRNET), Harare, Zimbabwe, 6-10 December 1993.*, AFRNET (African Feed Resources Network), Nairobi, Kenya.

Milford, R. (1967). Nutritive value and chemical composition of seven tropical legumes and lucerne grown in subtropical south-eastern queensland. *Aust. J. Exp. Agric. Anim. Husbandry*, 7:540–545.

Minson, D. J. (1990). *Forage in ruminant nutrition.* Academic Press, San Diego. pp. 483.

Minson, D. J. and McLeod, M. N. (1970). The digestibility of tropical and temperate grasses. In *Pro. XVI Int. Grassl. Congr.*, pages 719–722, Surfers Paradise, Queensland, Australia.

Mlay, P. S., Pereka, A., Chikula, P. E., Balthazary, S., Igusti, J., Hvelplund, T., Weisbjerg, M. R., and J, M. (2006). Feed value of selected tropical grasses, legumes and concentrates. *VETERINARSKI ARHIV*, 76(1):53–63.

MLD (1991). *Zero Grazing: A Handbook on technical aspects*. Ministry of Livestock Development. Nairobi, Kenya.

Moore, C. P. and Bushman, D. H. (1978). Potencial beef production on intensively managed elephant grass. In *Beef production on intensively managed elephant grass.*, pages 335–341. Centro Internacional de Agricultura Tropical (CIAT).

Morley, F. H. W. (1968). Pasture growth curves and grazing management. *Aust. J. Exp. Agric. Anim. Husbandry*, 8:40–45.

Mpairwe, D. R., Sabiiti, E. N., and Mugerwa, J. S. (1998). Effect of dried *Gliricidia sepium* leaf supplement on feed intake, digestibility and nitrogen retention in sheep fed dried KW4 elephant grass (*Pennisetum purpureum*) *ad libitum*. *Agrofor. Syst.*, 41:139–150.

Mpairwe, D. R., Sabiiti, E. N., Ummuna, N. N., Tegegne, A., and Osuji, P. (2003a). Integration of forage legumes with cereal crops. I. Effects of supplementation with graded levels of lablab hay on voluntary food intake, digestibility, milk yield and milk composition of crossbred cows fed maize-lablab stover or oats-vetch hay ad libitum. *Livestock Production Science*, 79(2-3):193–212.

Mpairwe, D. R., Sabiiti, E. N., Ummuna, N. N., Tegegne, A., and Osuji, P. (2003b). Integration of forage legumes with cereal crops: II. Effect of supplementation with lablab hay and incremental levels of wheat bran on voluntary food intake, digestibility, milk yield and milk composition of crossbred cows fed maize-lablab stover or oats-vetch hay ad libitum. *Livestock Production Science*, 79(2-3):213–226.

Muia, J. M. K., Tamminga, S., and Mbugua, P. N. (2000a). Effect of supplementing napier grass (*Pennisetum purpureum*) with sunflower meal or poultry litter-based concentrates on feed intake, live-weight changes and economics of milk production in Friesian cows. *Livestock Production Science*, 67(1-2):89–99.

Muia, J. M. K., Tamminga, S., Mbugua, P. N., and Kariuki, J. N. (1999). Optimal stage of maturity for feeding napier grass (*Pennisetum purpureum*) to dairy cows in kenya. *Tropical Grasslands*, 33:182Ű190.

Muia, J. M. K., Tamminga, S., Mbugua, P. N., and Kariuki, J. N. (2000b). The nutritive value of napier grass (*Pennisetum purpureum*) and its potential for milk production with or without supplementation: a review. *Tropical Science*, 40:1–23.

Muia, J. M. K., Tamminga, S., Mbugua, P. N., and Kariuki, J. N. (2001a). Effect of supplementing napier grass (*Pennisetum purpureum*) with poultry litter and sunflower meal based concentrates on feed intake and rumen fermentation in Friesian steers. *Animal Feed Science and Technology*, 92(1-2):113–126.

Muia, J. M. K., Tamminga, S., Mbugua, P. N., and Kariuki, J. N. (2001b). Rumen degradation and estimation of microbial protein yield and intestinal digestion of napier grass (*Pennisetum purpureum*) and various concentrates. *Animal Feed Science and Technology*, 93(3-4):177–192.

Mupangwa, J. F., Ngongoni, N. T., and Hamudikuwanda, H. (2006). The effect of stage of growth and method of drying fresh herbage on chemical composition of three tropical herbaceous forage legumes. *Tropical and Subtropical Agroecosystems*, 6:23–30.

Mupangwa, J. F., Ngongoni, N. T., Topps, J. H., Acamovic, T., and Hamudikuwanda, H. (2003). Rumen degradability and post-ruminal digestion of dry matter, nitrogen and amino acids in three tropical forage legumes estimated by the mobile nylon bag technique. *Livestock Production Science*, 79(1):37–46.

Murphy, A. M. and Colucci, P. E. (1999). A tropical forage solution to poor quality ruminant diets: A review of *Lablab purpureus*. *Livestock Research for rural Development*, Volume 11, Issue No.2:Retrieved June 11, 2008, from http://www.cipav.org.co/lrrd/lrrd11/2/colu.htm.

Murray, J. D. (2002). *Mathematical biology. I. An introduction.* Springer-Verlag, 3rd edition.

Murwira, K. H., Swift, M. J., and Frost, P. G. H. (1995). Manure as a key resource in sustainable agriculture. In Powell, J. M., Fernandez-Rivera, S., Williams, T. O., and Renard, C., editors, *Livestock and sustainable nutrient cycling in mixed farming systems of Sub-Saharan Africa. Proceedings of an International Conference, 22-26 November 1993. International livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia. Vol. II: Technical Papers*, pages 131–148.

Muwanga, J. W. (1994). An economic Evaluation of Zero-grazing dairy production systems in Uganda: A case study of Mpigi and Mukono Districts. Master's thesis, MSc. Thesis. Makerere University, Kampala, Uganda.

Nahdy, S. (2001). Decentralization of services in Uganda, The formation of National Agricultural Advisory Services (NAADS). In Rangnekar, D. and Thorpe, W., editors, *Proceedings of a smallholder dairy production and marketing - opportunities and constraints south-south workshop held at National Dairy Development Board, Anand, India, from 13th to 16th March 2001*.

Nakiganda, A., Mcleod, A., Bua, A., Phipps, R., Upton, M., and Taylor, N. (2006). Farmers' constraints, objectives and achievements in smallholder dairy systems in Uganda. *Livestock*

*Research for Rural Development*, volume 18, Article No. 69:Retrieved July 10, 2008, from http://www.lrrd.org/lrrd18/5/naki18069.htm.

Nennich, T. D., Harrison, J. H., VanWieringen, L. M., Meyer, D., Heinrichs, A. J., Weiss, W. P., St-Pierre, N. R., Kincaid, R. L., Davidson, D. L., and Block, E. (2005). Prediction of manure and nutrient excretion from dairy cattle. *J Dairy Sci*, 88(10):3721–3733.

Nennich, T. D., Harrison, J. H., VanWieringen, L. M., St-Pierre, N. R., Kincaid, R. L., Wattiaux, M. A., Davidson, D. L., and Block, E. (2006). Prediction and evaluation of urine and urinary nitrogen and mineral excretion from dairy cattle. *J Dairy Sci*, 89(1):353–364.

Norton, B. W. and Poppi, D. P. (1995). Composition and Nutritional Attributes of Pasture Legumes. In D'Mello, J. P. F. and Devendra, C., editors, *Tropical Legumes in Animal Nutrition*, pages 23–47. CAB International, Wallingford, U.K.

NRC (1996). *Nutrient Requirements of Beef Cattle, 7th Revised Edition*. National Academy Press, Washington DC, USA.

Nurfeta, A., Tolera, A., Eik, L. O., and Sundstøl, F. (2008). The supplementary value of different parts of enset (ensete ventricosum) to sheep fed wheat straw and desmodium intortum hay. *Livestock Science*, 119(1-3):22 – 30.

Nworgu, F. C. and Ajayi, F. T. (2005). Biomass, dry matter yield, proximate and mineral composition of forage legumes grown as early dry season feeds. *Livestock Research for Rural Development*, 17(11).

Nyambati, E. M., Sollenberger, L. E., and Kunkle, W. E. (2003). Feed intake and lactation performance of dairy cows offered napiergrass supplemented with legume hay. *Livestock Production Science*, 83(2-3):179–189.

Ogwang, B. H. and Mugerwa, J. S. (1976). Yield response to N application and in vitro dry matter digestibility of elephant grass x bulrush millet hybrids. *East African Agricultural and Forestry Journal*, 41:231–242.

Ørskov, E. R. (1982). *Protein Nutrition in Runinants.* Academic Press, London.

OSSREA (1999). Dryland Husbandry in Uganda. In *Addis Ababa: II.Pastoral Resource Management In Mbarara District In Uganda: An Economic Assessment Paper 162*. DHP Publications Series, no 5.

Osuhor, C. U., Tanko, R. J., Dung, D. D., Muhammad, I. R., and Odunze, A. C. (2004). Water Consumption of Yankasa Rams Fed a Basal Diet of Maize Stover-lablab Mixture. *Pakistan Journal of Nutrition*, 3(3):154–157.

Pandey, S. and Hardaker, J. B. (1995). The Role of modelling in the quest for sustainable farming systems. *Agricultural Systems*, 47:439–450.

Paterson, J. A., Belyea, L. A., Bowman, J. P., Kerly, M. S., and Williams, J. E. (1994). The impact of forage quality and supplementation regimen on ruminant animal intake and performance. In Fahey, G. C., Collins, M., Mertens, D. R., and Moser, L. E., editors, *Forage quality, evaluation and utilization.*, pages 59–107. American Society of Agronomy, Crop Science Society of America and Soil Science Society of America, Madison, Wisconsin, USA.

Pell, A. N. (1999). Crop-Livestock Management Systemsin Sub-Saharan Africa. *Environment, Development and Sustainability*, 1:337–348.

Pilbeam, C. J., Tripathi, B. P., Sherchan, D. P., Gregory, P. J., and Gaunt, J. (2000). Nitrogen balances for households in the mid-hills of Nepal. *Agriculture, Ecosystems and Environment*, 79:61–72.

Powell, J. M., Fernandez-Rivera, S., Hiernaux, P., and Turner, M. D. (1996). Nutrient cycling in integrated rangeland/cropland systems of the Sahel. *Agricultural Systems*, 53:143–170.

Powell, J. M. and Valentin, C. (1998). Effects of livestock on soil fertility in West Africa. In Renard, C., Neef, A., Becker, K., and von Oppen, M., editors, *Soil Fertility Management in West African Land Use Systems*, pages 319–338. Margraf Verlag, Weikersheim, Germany.

Reid, R. L., Post, A. J., and Mugerwa, J. S. (1973). Studies on the nutritional qualities of grasses and legumes in Uganda. I. Application of in vitro digestibility techniques to species and stage of growth effects. *Trop. Agric. (Trinidad)*, 50:1–15.

Rickert, K. G., Stuth, J. W., and McKeon, G. M. (2000). Modelling Pasture and Animal Production. In L. 't Mannetje, L. and Jones, R. M., editors, *Field and Laboratory Methods for Grassland and Animal Production Research*, pages 29–66. CAB International.

Rotz, C. A., Buckmaster, D. R., and Comerford, J. W. (2005). A beef herd model for simulating feed intake, animal performance, and manure excretion in farm systems. *J Anim Sci*, 83(1):231–242.

Rotz, C. A., Satter, L. D., Mertens, D. R., and Muck, R. E. (1999). Feeding strategy, nitrogen cycling, and profitability of dairy farms. *J Dairy Sci*, 82(12):2841–2855.

Rufino, M. C., Rowe, E. C., Delve, R. J., and Giller, K. E. (2006). Nitrogen cycling efficiencies through resource-poor african crop-livestock systems. *Agriculture, Ecosystems & Environment*, 112(4):261 – 282.

Ruiz, T. M., Sanchez, W. K., Staples, C. R., and Sollenberger, L. E. (1992). Comparison of elephant grass silage and corn silage for lactating dairy cows. *J. Dairy Sci.*, 75:533–543.

Sanchez, P. A., Shepherd, K. D., Soule, M. J., Place, F. M., Buresh, R. J., Izac, A. M. N., Mokwunye, A. U., Kwesiga, F. R., Ndirutu, C. G., and Woomer, P. (1997). Soil fertility replenishment in Africa: An investment in natural resource capital. In Buresh, R. J., Sanchez, P. A., and Calhoun, F., editors, *Replenishing Soil Fertility in Africa*, pages 1–46. Soil Science Soc. of America. Madison, WI.

SCA (1990). *Feeding systems for Australian livestock: ruminants*. Standing subcommittee on Agriculture, Commonwealth Scientific and Industrial Research Organisation (CSIRO). CSIRO Publications, Melbourne, Australia.

Scherr, S. J. (1999). Soil Degradation: A Threat to Developing Country Food Security by 2020. Technical report, IFPRI, Washington, D.C.

Schlecht, E., Hiernaux, P., Achard, F., and Turner, M. D. (2004). Livestock related nutrient budgets within village territories in western Niger. *Nutrient Cycling in Agroecosystems*, 68(3):199–211.

Segel, L. A. (1972). Simplification and scaling. *SIAM. Rev.*, 14:547–571.

Sheldrick, W., Syers, J. K., and Lingard, J. (2003). Contribution of livestock excreta to nutrient balances. *Nutrient Cycling in Agroecosystems*, 66(2):119–131.

Sherpherd, K. D., Ohlsson, E., Okalebo, J. R., Ndufa, J. K., and David, S. (1995). A static model of nutrient flow on mixed farms in the highlands of western Kenya to explore the possible impact of improved management. In Powell, J. M., Fernández-Rivera, S., Williams, T. O., and Renard, C., editors, *Livestock and sustainable nutrient cycling in mixed farming systems of Sub-Saharan Africa. Proceedings of an International Conference, 22-26 November 1993. International livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia. Vol. II: Technical Papers*, pages 523–538.

Skerman, P. J. and Riveros, F. (1990). *Tropical grasses*. FAO Plant Production and Protection Series 23. Food and Agriculture Organization of the United Nations. Rome. pp. 832.

Sniffen, C. J., O'Connor, J. D., Van Soest, P. J., Fox, D. G., and Russell, J. B. (1992). A net carbohydrate and protein system for evaluating cattle diets: II. Carbohydrate and protein availability. *J. Anim. Sci.*, 70:3562–3577.

Sollenberger, L. E. and Jones, C. S. (1989). Beef production from N fertilized mott elephant grass. *Trop. Grassl.*, 23:129–134.

Sørensen, P., Weisbjerg, M. R., and Lund, P. (2003). Dietary effects on the composition and plant utilization of nitrogen in dairy cattle manure. *The Journal of Agricultural Science*, 141(01):79–91.

Stangel, P. (1995). Nutrient recycling and its importance in sustaining crop-livestock systems in Sub-Saharan Africa: An overview. In Powell, J., Fernandez-Rivera, S., Williams, T. O., and Renard, C., editors, *Livestock and sustainable nutrient cycling in mixed farming systems of Sub-Saharan Africa. Proceedings of an International Conference, 22-26 November 1993. International livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia. Vol. II: Technical Papers*, pages 63–82.

Stobbs, T. H. (1971). Production and composition of milk from cows grazing siratro (*Phaseolus atropurpureus*) and greenleaf desmodium (*Desmodium intortus*). *Aust. J. Exp. Agric. Anim. Husbandry*, 11:268–273.

Stobbs, T. H. and Thompson, P. A. C. (1975). Milk production from tropical pastures. *World Anim. Rev.*, 13:27–31.

Strogatz, S. H. (1994). *Nonlinear dynamics and chaos: with applications to physics, biology, chemistry, and engineering.* Perseus Books.

Stuth, J. W., Lyons, R. K., and Kreuter, U. P. (1995). Animal/plant interactions: Nutrient acquisition and use by ruminants. In Powell, J. M., Fernandez-Rivera, S., Williams, T. O., and Renard, C., editors, *Livestock and sustainable nutrient cycling in mixed farming systems of Sub-Saharan Africa. Proceedings of an International Conference, 22-26 November 1993. International livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia. Vol. II: Technical Papers*, pages 63–82.

Tamminga, S. (1979). Protein degradation in the forestomachs of ruminants. *J. Anim. Sci.*, pages 1615–1630.

Thomsen, I. K. (2000). C and N transformations in $^{15}$N cross-labelled solid ruminant manure during anaerobic and aerobic storage. *Bioresource Technology*, 72(3):267 – 274.

Thorne, P. J. and Tanner, J. C. (2002). Livestock and nutrient cycling in cro-animal systems in Asia. *Agricultural Systems*, 71:111–126.

Thornton, P. K. and Herrero, M. (2001). Integrated crop-livestock simulation models for scenario analysis and impact assessment. *Agricultural Systems*, 70:581–602.

Tibayungwa, F., Mugisha, J. Y. T., and Nabasirye, M. (2009). Dairy heifer growth and time to mating weight when fed elephant grass as sole feed: A simulation model. In Chilliard, Y., Glasser, F., Faulconnier, Y., Bocquier, F., Veissier, I., and Doreau, M., editors, *Ruminant physiology. Digestion, metabolism, and effects of nutrition on reproduction and welfare*, pages 782–783. Wageningen Academic Publishers, Wageningen, The Netherlands.

Tumutegyereize, K., Hyuha, T., and Sabiiti, E. N. (1999). Factors affecting dairy production in the peri-urban areas of Kampala. *Uganda Journal of Agricultural Sciences*, 4:7–11.

Twinamasiko, N. I. (2001). Dairy production. In Mukiibi, J. K., editor, *Agriculture in Uganda. Vol. IV: Livestock and Fisheries. 404 pp.*, pages 18–42. National Agricultural Research Organization-CTA-Fountain Publishers, Kampala, Uganda.

UBOS (2005). *Uganda Population and Housing Census Report*. Uganda Bureau of Statisics. Ministry of Finance, Planning and Economic Development.

Vaccaro, R. and Rivero, S. (1985). Growth of Holstein Friesian females in the Venezuelan tropics. *Animal Production*, 40:279–285.

Van Soest, P. J. (1994). *Nutritional ecology of the ruminant.* Cornell University Press., 2nd edition. pp. 476.

Von Kaufmann, R. R. (1999). Livestock development and research into the new millennium, ILRI working document. Technical report, International Livestock Research Institute, Nairobi, Kenya.

Walker, J. W. (1993). Nutritional models for grazing animals. *Buvisindi, Icelandic Agricultural Sciences*, 7:45–57.

Wang, S. J., Fox, D. G., Cherney, D. J. R., Chase, L. E., and Tedeschi, L. O. (2000). Whole-Herd Optimization with the Cornell Net Carbohydrate and Protein System. III. Application of optimization model to evaluate alternatives to reduce nitrogen and phosphorus mass balance. *J. Dairy Sci.*, 83:2160–2169.

Webster, A. J. F. (1993). The metabolizable protein system for ruminants. In Haresign, W. and Garnsworthy, P. C., editors, *Recent advances in animal nutrition - 1992*, pages 93–110. Butterworths, London, UK.

Werblow, U. (1997). A radically changing world: Globalisation and food security up to the year 2020. *Agriculture and Rural Development*, 4(2):7–9.

Wickham, I. D., Wake, G. C., Woodward, S. J. R., and Thorrold, B. S. (1997). Dynamical systems modelling of the interactions of animal stocking density and soil fertility in grazed pasture. *J. Appl. Mathematics & Decision Sciences.*, 1(1):27–43.

Wilkerson, V. A., Mertens, D. R., and Casper, D. P. (1997). Prediction of excretion of manure and nitrogen by Holstein dairy cattle. *J Dairy Sci*, 80(12):3193–3204.

Woelcke, J., Berger, T., and Park, T. (2002). Institutional Market Reform and Nutrient Depletion: A Model for Soil Degradation in Uganda. *ZEFnews No. 11 December*.

Woodard, K. R. and Prine, G. M. (1991). Forage yield and nutritive value of elephant grass as affected by harvesting frequency and genotype. *Agron. J.*, 83:541–546.

Woodward, S. J. R. (1998). Dynamical systems models and their application to optimizing grazing management. In Peart, R. M. and Curry, R. B., editors, *Agricultural Systems Modeling and Simulation*, pages 419–473. Marcel Dekker Inc., New York.

Wouters, A. P. (1987). *Dry matter yield and quality of Napier grass on farm level 1983-1986.* Research report. Ministry of Livestock Development, Nairobi, Kenya. pp. 39.

Zanton, G. I. and Heinrichs, A. J. (2008). Analysis of Nitrogen Utilization and Excretion in Growing Dairy Cattle. *J. Dairy Sci.*, 91(4):1519–1533.

APPENDIX A

# Dimensional analysis code

The Forage growth and stocking level

$y = Y/K, \delta = c/K, \beta = rn/Ka$

$\mathrm{dY/dt} == aY(1 - Y/K) - n(rY)/(c+Y)$

$\frac{\mathrm{dY}}{\mathrm{dt}} == -\frac{nrY}{c+Y} + aY\left(1 - \frac{Y}{K}\right)$

$\frac{dY}{\mathrm{dt}} == -\frac{nrY}{c+Y} + aY\left(1 - \frac{Y}{K}\right)/.Y \to yK$

$\frac{dKy}{\mathrm{dt}} == aK(1-y)y - \frac{Knry}{c+Ky}$

$\frac{\mathrm{dy}K}{dt} == aK(1-y)y - \frac{Knry}{c+Ky}/.t \to \tau/a$

$\frac{a\mathrm{dy}K}{d\tau} == aK(1-y)y - \frac{Knry}{c+Ky}$

$\frac{a\mathrm{dy}K}{\mathrm{d}\tau}\Big/(aK) == aK(1-y)y/(aK) - \frac{Knry}{c+Ky}\Big/(aK)$

$\frac{\mathrm{dy}}{\mathrm{d}\tau} == (1-y)y - \frac{nry}{a(c+Ky)}$

$\frac{\mathrm{dy}}{\mathrm{d}\tau} == (1-y)y - \frac{nry}{a(c+Ky)}/.c \to \delta K$

$\frac{\mathrm{dy}}{\mathrm{d}\tau} == (1-y)y - \frac{nry}{a(Ky+K\delta)}$

$\frac{\mathrm{dy}}{\mathrm{d}\tau} == (1-y)y - \frac{nry}{a(\delta K+Ky)}/.r \to \beta aK/n$

$\frac{\mathrm{dy}}{\mathrm{d}\tau} == (1-y)y - \frac{Ky\beta}{Ky+K\delta}$

Cancel$\left[\frac{\beta Ky}{\delta K+Ky}\right]$

$\frac{y\beta}{y+\delta}$

$\frac{\mathrm{dy}}{\mathrm{d}\tau} == (1-y)y - \frac{\beta y}{\delta + y}$

$\frac{\mathrm{dy}}{\mathrm{d}\tau} == (1-y)y - \frac{y\beta}{y + \delta}$

---------------------------------------------------

The forage growth and liveweight gain model

$\mathrm{Clear}[\mathrm{dY}, \mathrm{dy}, \mathrm{dt}, \mathrm{d}\tau, \mathrm{dL}, \mathrm{dl}, a, Y, K, n, L, f, c, m, v]$

$y = Y/K, \tau = ta, \delta = c/K, \beta = f/av, l = Lv/K, \alpha = m/av$

Pasture growth

$\frac{\mathrm{dY}}{\mathrm{dt}} == aY\left(1 - \frac{Y}{K}\right) - L\frac{f\,Y}{c+Y}$

$\frac{\mathrm{dY}}{\mathrm{dt}} == -\frac{fLY}{c+Y} + aY\left(1 - \frac{Y}{K}\right)$

$\frac{\mathrm{dY}}{\mathrm{dt}} == -\frac{fLY}{c+Y} + aY\left(1 - \frac{Y}{K}\right) /. L \to lK/v$

$\frac{\mathrm{dY}}{\mathrm{dt}} == -\frac{fKlY}{v(c+Y)} + aY\left(1 - \frac{Y}{K}\right)$

$\frac{dY}{\mathrm{dt}} == -\frac{fKlY}{v(c+Y)} + aY\left(1 - \frac{Y}{K}\right) /. Y \to yK$

$\frac{dKy}{\mathrm{dt}} == aK(1-y)y - \frac{fK^2ly}{v(c+Ky)}$

$\frac{\mathrm{dy}K}{dt} == aK(1-y)y - \frac{fK^2ly}{v(c+Ky)} /. t \to \tau/a$

$\frac{a\mathrm{dy}K}{d\tau} == aK(1-y)y - \frac{fK^2ly}{v(c+Ky)}$

$\frac{a\mathrm{dy}K}{\mathrm{d}\tau} \Big/ (aK) == aK(1-y)y/(aK) - \frac{fK^2ly}{v(c+Ky)} \Big/ (aK)$

$\frac{\mathrm{dy}}{\mathrm{d}\tau} == (1-y)y - \frac{fKly}{av(c+Ky)}$

$\frac{\mathrm{dy}}{\mathrm{d}\tau} == (1-y)y - \frac{fKly}{av(c+Ky)} /. c \to \delta K$

$\frac{\mathrm{dy}}{\mathrm{d}\tau} == (1-y)y - \frac{fKly}{av(\delta K + Ky)}$

$\mathrm{Cancel}\left[\frac{fKly}{av(\delta K + Ky)}\right]$

$\frac{fly}{av(\delta + y)}$

$\frac{\mathrm{dy}}{\mathrm{d}\tau} == (1-y)y - \frac{fly}{av(\delta + y)}$

$\frac{\text{dy}}{\text{d}\tau} == (1-y)y - \frac{fly}{av(\delta+y)}$

$\frac{\text{dy}}{\text{d}\tau} == (1-y)y - \frac{fly}{av(\delta+y)} /. f \to \beta av$

$\frac{\text{dy}}{\text{d}\tau} == (1-y)y - \frac{\beta ly}{\delta+y}$

Liveweight gain

$\text{Clear}[\text{dY}, \text{dy}, \text{dt}, \text{d}\tau, \text{dL}, \text{dl}, a, Y, K, n, L, f, c, m, v]$

$\text{dL}/\text{dt}{==} - \frac{Lm}{v} + 1/vL\frac{f\,Y}{c+Y}$

$\frac{\text{dL}}{\text{dt}} == -\frac{Lm}{v} + \frac{fLY}{v(c+Y)}$

$\frac{dL}{\text{dt}} == -\frac{Lm}{v} + \frac{fLY}{v(c+Y)} /. L \to lK/v$

$\frac{dKl}{\text{dt}v} == -\frac{Klm}{v^2} + \frac{fKlY}{v^2(c+Y)}$

$\frac{\text{dl}K}{dtv} == -\frac{Klm}{v^2} + \frac{fKlY}{v^2(c+Y)} /. t \to \tau/a$

$\frac{a\text{dl}K}{dv\tau} == -\frac{Klm}{v^2} + \frac{fKlY}{v^2(c+Y)}$

$\frac{a\text{dl}K}{\text{d}\tau v} == -\frac{Klm}{v^2} + \frac{fKlY}{v^2(c+Y)} /. Y \to yK$

$\frac{a\text{dl}K}{\text{d}\tau v} == -\frac{Klm}{v^2} + \frac{fK^2ly}{v^2(c+Ky)}$

$\frac{a\text{dl}K}{\text{d}\tau v} == -\frac{Klm}{v^2} + \frac{fK^2ly}{v^2(c+Ky)} /. c \to \delta K$

$\frac{a\text{dl}K}{\text{d}\tau v} == -\frac{Klm}{v^2} + \frac{fK^2ly}{v^2(\delta K+Ky)}$

$\text{Cancel}\left[\frac{fK^2ly}{v^2(\delta K+Ky)}\right]$

$\frac{fKly}{v^2(\delta+y)}$

$\frac{a\text{dl}K}{\text{d}\tau v} == -\frac{Klm}{v^2} + \frac{fKly}{v^2(\delta+y)}$

$\frac{a\text{dl}K}{\text{d}\tau v} == -\frac{Klm}{v^2} + \frac{fKly}{v^2(\delta+y)}$

$\frac{a\text{dl}K}{\text{d}\tau v} \Big/ (aK) == -\frac{Klm}{v^2} \Big/ (aK) + \frac{fKly}{v^2(\delta+y)} \Big/ (aK)$

$\frac{\text{dl}}{\text{d}\tau v} == -\frac{lm}{av^2} + \frac{fly}{av^2(\delta+y)}$

$\frac{\text{dl}}{\text{d}\tau v} == -\frac{lm}{av^2} + \frac{fly}{av^2(\delta+y)} /. f \to a\beta v$

$\frac{\text{dl}}{\text{d}\tau v} == -\frac{lm}{av^2} + \frac{\beta ly}{v(\delta+y)}$

$\frac{\mathrm{dl}}{\mathrm{d}\tau v} == -\frac{lm}{av^2} + \frac{\beta l y}{v(\delta+y)} /.m \to \alpha a v$

$\frac{\mathrm{dl}}{\mathrm{d}\tau v} == \frac{\beta l y}{v(\delta+y)} - \frac{l\alpha}{v}$

$\frac{\mathrm{dl}}{\mathrm{d}\tau v} * v == \frac{\beta l y}{v(\delta+y)} * v - \frac{l\alpha}{v} * v$

$\frac{\mathrm{dl}}{\mathrm{d}\tau} == \frac{\beta l y}{\delta+y} - l\alpha$

---

The Forage-animal-nutrient model

$x = S/k_1$ , $y = V/k_1$ , $z = N/k_1$ , $\tau = at, \alpha = F/(ak_1)$ ,
$\beta = g/a, \gamma = c/a, \delta = f/a, \eta = b/a, \rho = K_s/k_1$

$\mathrm{dS}/\mathrm{dt} == F - aS - gSV/(K_s + S) + kcV$

$\frac{\mathrm{dS}}{\mathrm{dt}} == F - aS + ckV - \frac{gSV}{S+K_s}$

$\frac{dS}{\mathrm{dt}} == F - aS + ckV - \frac{gSV}{S+K_s} /.S \to x\, k_1$

$\frac{dxk_1}{\mathrm{dt}} == F + ckV - axk_1 - \frac{gVxk_1}{xk_1+K_s}$

$\frac{\mathrm{dx}k_1}{\mathrm{dt}} == F + ckV - axk_1 - \frac{gVxk_1}{xk_1+K_s} /.V \to yk_1$

$\frac{\mathrm{dx}k_1}{\mathrm{dt}} == F - axk_1 + ckyk_1 - \frac{gxyk_1^2}{xk_1+K_s}$

$\frac{\mathrm{dx}k_1}{\mathrm{dt}} == F - axk_1 + ckyk_1 - \frac{gxyk_1^2}{xk_1+K_s} /.F \to \alpha a k_1$

$\frac{\mathrm{dx}k_1}{\mathrm{dt}} == -axk_1 + ckyk_1 + a\alpha k_1 - \frac{gxyk_1^2}{xk_1+K_s}$

$\frac{\mathrm{dx}k_1}{dt} == -axk_1 + ckyk_1 + a\alpha k_1 - \frac{gxyk_1^2}{xk_1+K_s} /.t \to \tau/a$

$\frac{a\mathrm{dx}k_1}{d\tau} == -axk_1 + ckyk_1 + a\alpha k_1 - \frac{gxyk_1^2}{xk_1+K_s}$

$\frac{a\mathrm{dx}k_1}{\mathrm{d}\tau}/(ak_1) == -axk_1/(ak_1) + ckyk_1/(ak_1) + a\alpha k_1/(ak_1) - \frac{gxyk_1^2}{xk_1+K_s}/(ak_1)$

$\frac{\mathrm{dx}}{\mathrm{d}\tau} == -x + \frac{cky}{a} + \alpha - \frac{gxyk_1}{a(xk_1+K_s)}$

$\frac{\mathrm{dx}}{\mathrm{d}\tau} == -x + \frac{cky}{a} + \alpha - \frac{gxyk_1}{a(xk_1+K_s)} /.c \to \gamma a$

$\frac{\mathrm{dx}}{\mathrm{d}\tau} == -x + \alpha + ky\gamma - \frac{gxyk_1}{a(xk_1+K_s)}$

$\frac{\mathrm{dx}}{\mathrm{d}\tau} == \frac{\mathrm{dx}}{\mathrm{d}\tau} == -x + \alpha + ky\gamma - \frac{gxyk_1}{a(xk_1+K_s)} /.g \to \beta a$

$\frac{\mathrm{dx}}{\mathrm{d}\tau} == -x + \alpha + ky\gamma - \frac{xy\beta k_1}{xk_1+K_s}$

$\frac{\mathrm{dx}}{\mathrm{d}\tau} == -x + \alpha + ky\gamma - \frac{xy\beta k_1}{xk_1+K_s} /. K_s \to k_1\rho$

$\frac{\mathrm{dx}}{\mathrm{d}\tau} == -x + \alpha + ky\gamma - \frac{xy\beta k_1}{xk_1+\rho k_1}$

$\text{Cancel}\left[\frac{xy\beta k_1}{xk_1+\rho k_1}\right]$

$\frac{xy\beta}{x+\rho}$

$\frac{\mathrm{dx}}{\mathrm{d}\tau} == -x + \alpha + ky\gamma - \frac{xy\beta}{x+\rho}$

$\frac{\mathrm{dx}}{\mathrm{d}\tau} == -x + \alpha + ky\gamma - \frac{xy\beta}{x+\rho}$

---------------------------------------------------------------

$\mathrm{dV/dt} == gSV/(K_s+S) - cV - (fNV)/(k_1+V)$

$\frac{\mathrm{dV}}{\mathrm{dt}} == -cV - \frac{fNV}{V+k_1} + \frac{gSV}{S+K_s}$

$\frac{dV}{\mathrm{dt}} == -cV - \frac{fNV}{V+k_1} + \frac{gSV}{S+K_s} /. V \to yk_1$

$\frac{dyk_1}{\mathrm{dt}} == -cyk_1 - \frac{fNyk_1}{k_1+yk_1} + \frac{gSyk_1}{S+K_s}$

$\frac{\mathrm{dy}k_1}{dt} == -cyk_1 - \frac{fNyk_1}{k_1+yk_1} + \frac{gSyk_1}{S+K_s} /. t \to \tau/a$

$\frac{a\mathrm{dy}k_1}{d\tau} == -cyk_1 - \frac{fNyk_1}{k_1+yk_1} + \frac{gSyk_1}{S+K_s}$

$\frac{a\mathrm{dy}k_1}{\mathrm{d}\tau} == -cyk_1 - \frac{fNyk_1}{k_1+yk_1} + \frac{gSyk_1}{S+K_s} /. N \to zk_1$

$\frac{a\mathrm{dy}k_1}{\mathrm{d}\tau} == -cyk_1 - \frac{fyzk_1^2}{k_1+yk_1} + \frac{gSyk_1}{S+K_s}$

$\frac{a\mathrm{dy}k_1}{\mathrm{d}\tau} == -cyk_1 - \frac{fyzk_1^2}{k_1+yk_1} + \frac{gSyk_1}{S+K_s} /. S \to xk_1$

$\frac{a\mathrm{dy}k_1}{\mathrm{d}\tau} == -cyk_1 - \frac{fyzk_1^2}{k_1+yk_1} + \frac{gxyk_1^2}{xk_1+K_s}$

$\frac{a\mathrm{dy}k_1}{\mathrm{d}\tau}/(ak_1) == -cyk_1/(ak_1) - \frac{fyzk_1^2}{k_1+yk_1}/(ak_1) + \frac{gxyk_1^2}{xk_1+K_s}/(ak_1)$

$\frac{\mathrm{dy}}{\mathrm{d}\tau} == -\frac{cy}{a} - \frac{fyzk_1}{a(k_1+yk_1)} + \frac{gxyk_1}{a(xk_1+K_s)}$

$\frac{\mathrm{dy}}{\mathrm{d}\tau} == -\frac{cy}{a} - \frac{fyzk_1}{a(k_1+yk_1)} + \frac{gxyk_1}{a(xk_1+K_s)} /. c \to \gamma a$

$\frac{\mathrm{dy}}{\mathrm{d}\tau} == -y\gamma - \frac{fyzk_1}{a(k_1+yk_1)} + \frac{gxyk_1}{a(xk_1+K_s)}$

$\frac{\mathrm{dy}}{\mathrm{d\tau}} == -y\gamma - \frac{fyzk_1}{a(k_1+yk_1)} + \frac{gxyk_1}{a(xk_1+K_s)}/.g \to \beta a$

$\frac{\mathrm{dy}}{\mathrm{d\tau}} == -y\gamma - \frac{fyzk_1}{a(k_1+yk_1)} + \frac{xy\beta k_1}{xk_1+K_s}$

$\frac{\mathrm{dy}}{\mathrm{d\tau}} == -y\gamma - \frac{fyzk_1}{a(k_1+yk_1)} + \frac{xy\beta k_1}{xk_1+K_s}/.f \to \delta a$

$\frac{\mathrm{dy}}{\mathrm{d\tau}} == -y\gamma - \frac{yz\delta k_1}{k_1+yk_1} + \frac{xy\beta k_1}{xk_1+K_s}$

$\frac{\mathrm{dy}}{\mathrm{d\tau}} == -y\gamma - \frac{yz\delta k_1}{k_1+yk_1} + \frac{xy\beta k_1}{xk_1+K_s}/.K_s \to k_1\rho$

$\frac{\mathrm{dy}}{\mathrm{d\tau}} == -y\gamma - \frac{yz\delta k_1}{k_1+yk_1} + \frac{xy\beta k_1}{xk_1+\rho k_1}$

$\mathrm{Cancel}\left[\frac{yz\delta k_1}{k_1+yk_1} + \frac{xy\beta k_1}{xk_1+\rho k_1}\right]$

$\frac{yz\delta}{1+y} + \frac{xy\beta}{x+\rho}$

$\frac{\mathrm{dy}}{\mathrm{d\tau}} == -y\gamma - \frac{yz\delta}{1+y} + \frac{xy\beta}{x+\rho}$

$\frac{\mathrm{dy}}{\mathrm{d\tau}} == -y\gamma - \frac{yz\delta}{1+y} + \frac{xy\beta}{x+\rho}$

------------------------------------------------------

$\mathrm{dN/dt}==(fNV)/(k_1+V)-bN$

$\frac{\mathrm{dN}}{\mathrm{dt}} == -bN + \frac{fNV}{V+k_1}$

$\frac{dN}{\mathrm{dt}} == -bN + \frac{fNV}{V+k_1}/.N \to zk_1$

$\frac{dzk_1}{\mathrm{dt}} == -bzk_1 + \frac{fVzk_1}{V+k_1}$

$\frac{\mathrm{dz}k_1}{dt} == -bzk_1 + \frac{fVzk_1}{V+k_1}/.t \to \tau/a$

$\frac{a\mathrm{dz}k_1}{d\tau} == -bzk_1 + \frac{fVzk_1}{V+k_1}$

$\frac{a\mathrm{dz}k_1}{\mathrm{d\tau}} == -bzk_1 + \frac{fVzk_1}{V+k_1}/.V \to yk_1$

$\frac{a\mathrm{dz}k_1}{\mathrm{d\tau}} == -bzk_1 + \frac{fyzk_1^2}{k_1+yk_1}$

$\frac{a\mathrm{dz}k_1}{\mathrm{d\tau}}/(ak_1) == -bzk_1/(ak_1) + \frac{fyzk_1^2}{k_1+yk_1}/(ak_1)$

$\frac{\mathrm{dz}}{\mathrm{d\tau}} == -\frac{bz}{a} + \frac{fyzk_1}{a(k_1+yk_1)}$

$\frac{\mathrm{dz}}{\mathrm{d\tau}} == -\frac{bz}{a} + \frac{fyzk_1}{a(k_1+yk_1)}/.f \to \delta a$

$$\frac{\mathrm{dz}}{\mathrm{d}\tau} == -\frac{bz}{a} + \frac{yz\delta k_1}{k_1 + yk_1}$$

$$\frac{\mathrm{dz}}{\mathrm{d}\tau} == -\frac{bz}{a} + \frac{yz\delta k_1}{k_1 + yk_1} /. b \to \eta a$$

$$\frac{\mathrm{dz}}{\mathrm{d}\tau} == -z\eta + \frac{yz\delta k_1}{k_1 + yk_1}$$

$$\mathrm{Cancel}\left[\frac{yz\delta k_1}{k_1 + yk_1}\right]$$

$$\frac{yz\delta}{1+y}$$

$$\frac{\mathrm{dz}}{\mathrm{d}\tau} == -z\eta + \frac{yz\delta}{1+y}$$

$$\frac{\mathrm{dz}}{\mathrm{d}\tau} == \frac{yz\delta}{1+y} - z\eta$$

APPENDIX B

# Computer code for simulating dynamical systems

Forage growth, intake and stocking density system

```
init y=0.2, l=0.8
y'=y*(1-y) - (beta*l*y)/(delta+y)
l'= (beta*l*y)/(delta+y) - alpha*l
par beta=0.5, delta=0.3, alpha=0.2
@ total=400,dt=.05,xhi=1.5,yhi=1.1, xlo=0,ylo=0,bounds=150000
done
----------------------------------------------------
```

Forage growth, intake and liveweight gain system

```
init y=0.2, l=0.8
y'=y*(1-y) - (beta*l*y)/(delta+y)
l'= (beta*l*y)/(delta+y) - alpha*l
par beta=0.5, delta=0.3, alpha=0.2
@ total=400,dt=.05,xhi=1.5,yhi=1.1, xlo=0,ylo=0,bounds=150000
done
---------------------------------------------------
```

Forage-animal-nutrient system

```
init x=.15,y=1,z=3
x'=alpha-x+(k*Y*gamma)-(x*y*beta)/(x+rho)+z*nu
y'=(x*y*beta)/(x+rho)-(y*gamma)-(y*z*delta)/(1+y)
z'=(y*z*delta)/(1+y)-z*nu
par alpha=1,k=.5,gamma=.1,beta=1,rho=.5,delta=.2,nu=.1
@ dt=.125, total=1000, xplot=x, yplot=y, zplot=z, axes=3d
@ xmin=-0.1,xmax=1.2,ymin=-0.1,ymax=10,zmin=-0.1,zmax=11,bounds=150000
@ xlo=-1.5,ylo=-2,xhi=1.5,yhi=2
done
-------------------------------------------------
```

APPENDIX C

# Published papers

1. Tibayungwa, F., Mugisha, J. Y. T., and Nabasirye, M. (2010a). Modeling growth of dairy cattle heifers fed elephant grass under stall-feeding system in uganda. *African Journal of Agricultural Research*, 5(11):1220-1227.

2. Tibayungwa, F., Mugisha, J. Y. T., and Nabasirye, M. (2010b). Modelling nitrogen excretion, elephant grass growth and animal production in a stall-feeding dairy system. *African Journal of Agricultural Research*, 5(15):2039-2044.

3. Tibayungwa, F., Mugisha, J. Y. T., and Nabasirye, M. (2010). Modelling the effect of supplementing elephant grass with *Lablab purpureus* and *Desmodium spp* on weight gain of dairy heifers under stall-feeding system. *African Journal of Agricultural Research*, Accepted.

4. Tibayungwa, F., Mugisha, J. Y. T., and Nabasirye, M. (2010). Qualitative analysis of livestock-forage system in the stall-feeding smallholder dairy cattle system. *African Journal of Agricultural Research*, Accepted.

5. Tibayungwa, F., Mugisha, J. Y. T., and Nabasirye, M. (2009). Dairy heifer growth and time to mating weight when fed elephant grass as sole feed: A simulation model. In: Chilliard, Y., Glasser, F., Faulconnier, Y., Bocquier, F., Veissier, I., and Doreau, M. (Eds.), Ruminant physiology. Digestion, metabolism, and effects of nutrition on reproduction and welfare, pages 782-783. Wageningen Academic Publishers, Wageningen, The Netherlands.