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MODELLING OF ECOLOGICAL AND ECONOMIC SUSTAINABILITY OF A PASTORAL PRODUCTION SYSTEM IN UGANDA

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Dissertation

Zur Erlangung des Doktorgrades

Der Universität für Bodenkultur

February 2010

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DEDICATION

To my late Mother Nanteza Annette, to my father Mulindwa Anthony, to my sister Nakirya Rita, to my wife Kaggwa Christine and to my daughter Namayengo Xavier Martha

ACKNOWLEDGEMENTS

First and foremost, I thank God the Almighty for his gifts and strength that enabled me to complete this study.

I would like to record a special note of thanks to my main supervisor Univ. Prof. Sölkner Johann, who generously devoted his time, giving valuable suggestions and tirelessly commented on the draft. His sincere advice in reshaping and organizing the whole dissertation was great.

I would like also to express my deepest gratitude to other members of the supervision team, Dr. Maria Wurzinger, Dr. A.M OKeyo, Dr. Herrero Mario and Dr. Julie Ojango for sharing their time and expertise and views. Dr. Maria not only supervised my study but also did a lot of administrative work that helped me settle in a new environment.

I am grateful to Dr. Mort M. Kothmann, of T&M University for sending me relevant literature via emails even though we are strangers to each other. Special thanks go to Dr. Ssewanyana Edward for the logistical support through provision of a vehicle whenever I needed it for field work.

I wish to thank Dr. Mpairwe Denis, of Makerere University for the technical advice about the state of pasture management in the study area as well as providing pasture data that was useful during the evaluation of model outputs of my study.

I am grateful for the financial support by Austrian Development Agency (ADA) through the International Livestock Research Institute (Nairobi) that enabled me to undertake this training. I am equally grateful to the Director General, NARO and Director of Research, National Semi Arid Resources Research Institute (NASARRI), Serere and the Director of Research, National Livestock Resources Research Institute (NALIRI), Tororo for their support and permission to allow me undertake the training. For colleagues at NALIRI and NASARRI: James, Joseph, Moses, David, Abila, Carol,

Jackson and Nalumoso. I thank you all for the encouragement and the many various ways you assisted me.

I thank the staff of NAGRIC, Entebbe especially Dr.Ssemambo, Dr.Arthur, Sserwanja and Nathan for their support.

I appreciate the comradeship and encouragement I experienced from the graduate students: Tadelles, Gameda, Hitaye, Amlaku, Luis, Astrid, Romana, Florian, Bett, Albert, Philip, Lina, Keneddy, Eddy, Maria, Wendo, Paul, Fredrick and the staff of the Department of Sustainable Agricultural Systems, Division of Livestock Sciences at BOKU.

Special thanks go to my fellow graduate student Galukande Esau, who did most of the donkey work to generate parameters used in my study and for the good working relationship. I wish to thank Dr.Assimwe and Dr.Ssemuyaba for the good working relationship and for taking part in the process of data collection. Thanks go to all the farmers that participated in the study.

I am grateful to the staff of ILRI, Nairobi, Judy, James, Joshua, and Dr. Ojango Julie for the assistance they offered me during my stay at ILRI.

I would also like to thank all my friends in the Ugandan community in Vienna, Solomon, Steven, Ssozi, Nantongo, Mulla, Mazune and Assimwe family for making me comfortable during my stay in Vienna.

Finally, I am deeply obligated to the members of my family Rita, Brian, John, Allan, Brenda, Denis, Bridget, Richard, Bob, Susan, Robert, Donald and my grandmother Julian Nambi for their continued love and support. My sincere gratitude goes to my Dear wife, Christine for providing the moral and emotional support over the years and for the lonely times she endured during my studies especially my absence during the birth of our first born daughter Martha. I thank my parents for the life and support over the years and for allowing me to choose my career.

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CHAPTER I

1.0 General introduction

The Ankole pastoral production system in Uganda is characterized by extensive grazing but differs from other pastoral systems elsewhere in the sense that there is no communal grazing. Land is owned individually, in most cases under leasehold for 49 years. The production system comprises of large, medium and small scale ranching / farm enterprises, in terms of both land acreage and animal numbers. Milk is the main product of the pastoral households in Nyabushozi (Mugerwa 1992) but cattle are also kept for prestige, social and other cultural functions. In terms of production objectives, there is an on-going shift from traditional subsistence to commercial enterprises. While the traditional beliefs of prestigious large herds, minimum input and respect for the various roles performed by cattle are still pertinent, there is increasingly a strong desire to produce higher quality and more productive animals for the market. The sale of milk and live animals are the major sources of income for these households. When there is an emergency need of money, pastoralists will sell adult female animals, because the males are usually sold off as yearlings to meet routine family financial needs. The love for the local breed (the long horned Ankole cattle) notwithstanding, there is an emerging production system where farmers keep separate herds Ankole and Holstein Friesian x Ankole crosses leading to a steady increase in crossbred cattle in the system. Most households' long-term plans have an aspect of upgrading the herd for increased milk yields and improvement of the rangeland on which to graze the improved stock (Galukande et al., 2009). Recent studies (Alary et al., 2007; Serunkuuma, 1998 and Wurzinger et al., 2008) reported wide spread crossbreeding of Ankole cattle with Holstein Friesian bulls and separate herds consisting of pure Ankole and crossbred animals are common on farms, an undertaking that makes the system complex. Konandreas and Anderson (1982) noted that the long term survival of traditional livestock production systems within the rapidly evolving national economies of Africa will depend on their capacity to provide products in quantities and at prices which satisfy the subsistence and income needs of the livestock producers.

In the Ankole system, knowledge of the high management standards associated with keeping crossbred cattle is of paramount importance. The forage resources in Ankole pastoral systems are characterized by low levels of productivity per unit area (Okello et al., 2005) with high variability in yields, both within and across years. Individual herd managers have opportunities to improve the supply of forage to their herds at any given time but the liberty to move animals as the forage resources in one location are depleted is steadily reducing. The variability in the supply and quality of forage on offer compounds the variability inherent in the animal-level biological processes. Understanding the internal mechanisms for the interactions between major components such as forage, grazing animal, soil, water, and nutrient in a pastoral system, is essential to the development of good management practices that ensure productivity and environmental stewardship (Mohtar et al., 2000). Selecting an appropriate management strategy for a dairy production system requires an understanding of the system as a whole in its agro-ecological context, understanding of the inter-relationships between systems components and knowledge of the objectives of the farm manager (Herrero et al., 1999).

1.1 System analysis and simulation

Systems analysis defined as a body of theory and techniques for studying, describing, and making predictions about complex systems and characterized by use of advanced mathematical and statistical procedures and by use of computers (Grant et al., 1997). Simulation is defined as a process of using a model, or trace through step by step, the behaviour of the system being studied (Grant et al., 2000). Simulation models are composed of arithmetic and logical operations that together represent the structure (state) and behaviour (change of state) of the system of interest. If appropriate variables to describe the system are chosen and appropriately represent the rules governing change, then one is able to trace the state of the system through time, in which case the behaviour of the system can be simulated. The justification for model building and modification of existing models in systems research is that experimentation on real systems can be very site specific, time consuming and expensive. However, modeling cannot exist without data from observation and

experimentation, which is necessary to develop and validate models. Grassland utilization for dairy and beef production is an economically important production system and has been subjected to research for several decades. Because of the multidisciplinary characteristics, modeling presents a useful tool for organizing knowledge from the different disciplines and to transfer the knowledge further to the beef and dairy production in rangelands in terms of management strategies.

The nature of grazing systems presents a number of major difficulties for management-oriented research. The complexity of grazing systems and, indeed, of all farming systems, has resulted in the fragmented development of agricultural research into a number of highly specialized fields. If research is to be efficient, the results of the experimentation must be eventually evaluated in relation to the operational goals of the system to which the research is directed (Wright and Dent 1969).

Traditionally, experiments are designed to test a factor that influences 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 the complexity of a system increases the value of quantitative systems models also increases (Walker 1993). Several types of models are available in animal production varying from simple empirical to complex mechanistic models. Empirical models are those 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).

When faced with complex, multi-stakeholder environmental issues, system dynamics has the greatest potential when used in a participatory fashion by scientists and managers working together with others who also have a stake in land management decisions. Models, whether conceptual or mathematical, are an extremely useful way of representing the linkages and interactions that make up a real-life system, which is generally too complex to mentally grasp as a whole. By representing the quantifiable linkages between the different environmental and socio-economic elements in the human-environmental system, mathematical models improve understanding of the

system and the relative influence of each system element. However, the use of models in livestock research is not without hazard, as a model can only ever be a simplification of a real-life system. A good model must include the key system elements and relationships (Bart 1995; Deaton and Winebrake 1999), but it is not always clear what these are at the start of the modelling process. Biot (1993) suggested that modeling the behaviour of rangeland is preferable to an approach based solely on monitoring for the prediction of long-term responses to different management strategies. The value of modeling pastoral production systems is expected to be even greater because of the much greater reliance on range and pasture by livestock throughout the year.

1.3 Objective of the study

The overall objective of the study was to evaluate the Ankole pastoral system and determine conditions under which both or either one of the cattle genotypes could be kept on a sustainable basis. The specific objectives of this study were: (a) to analyze long-term productivity and economic viability of the emerging production system, b) Identify constraints to the emerging production system, and (c) develop a stochastic pastoral simulation model and use it to evaluate alternative management options to be recommended for use by livestock keepers.

1.4 General materials and methods

1.4.3 STELLA software and systems analysis

The system dynamics model used in this study was developed using the Structured Thinking Experiential Learning Laboratory Animation (STELLA 9.0.2. 2007) software. The software uses an iconographic interface to facilitate construction of dynamic systems models (Costanza et al., 1998) and it includes a procedural programming language that is used to view and analyze the equations that are created through the manipulation of the icons. STELLA has been developed by combining current advances in object-oriented programming with Forrester notation (Forrester 1968; 1969; 1971).

STELLA is based on the underlying logic of systems thinking (Richmond 2001) and allows for modeling various systems to generate simulated data that would account for the interconnections between the components. Essentially, it consists of three distinct layers: the interface layer, the map or model layer, and the equations layer. The model layer is where the modeler can use specific tools to create the model. The specific tools include stocks, flows, converters, connectors, and decision process diamonds similar to Forrester notation: stocks, flows and converters (Figure1.1). To explain these symbols an example of hypothetical population is used (Figure1.2). In this case stocks represent the population, flows represent the births and deaths, and the converters represent the birth and death rates.

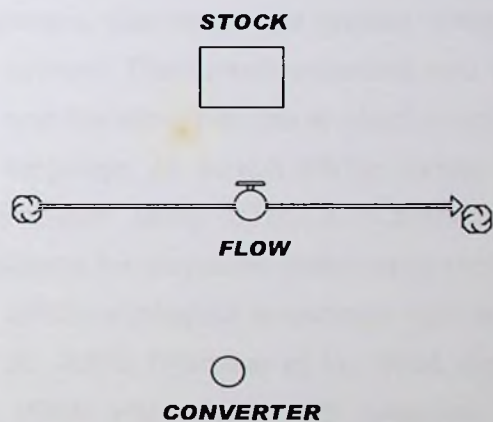


Figure1.1: System dynamics language symbols

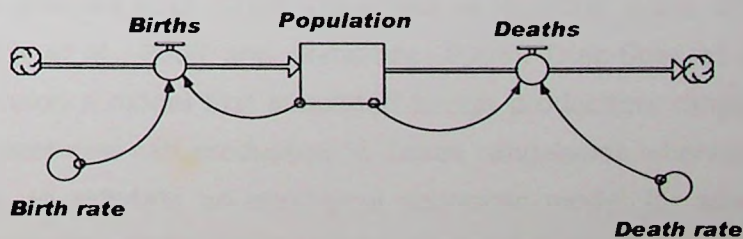


Figure 1.2: System dynamics model of a population

The stocks from an operational point of view are the accumulators and indicate the total amounts that they are accumulating in the time. Stocks can be thought of as a repository where something is accumulated, stored and potentially passed to other elements in the system (Deaton and Winebrake 1999). The flows are used to describe activities or changes causing modification of the stocks. From the perspective of the single reservoir flows can be positive (inflow) or negative (outflow). The converters modify the activities within the system. Unlike stocks, they do not represent an accumulation of anything, nor do they have any memory. The final element of the language are the connectors used to connect the stocks to the converters, the stocks to flows, flows to each other, converters to flows and converters to other converters. Converters are system variables that can play several different roles within a system. Their most important role is to dictate the rates at which the flows operate and therefore the rate at which stock contents change.

Given its programming language, an almost infinite variety of systems and dynamic relationships can be modeled using STELLA (Costanza et al., 1998). Models employing the Stella software for computer-aided simulation have been widely used in ecology (Sage *et al.*, 2003), ecological economics (Shi and Gill, 2005), population dynamics (Gertseva et al., 2003; Gertseva et al., 2004 and Walters 2001), climatic variations (Vitale et al., 2003) and organic acid dynamics (Van Hees et al., 2005). Chen et al. (1997) and Hitchcock et al. (1999) verified the suitability of the program in modeling nitrogen flow in dairy farm for waste management and nutrient dynamics from land applied animal manure, respectively. While Montoya et al. (1999) simulated nitrogen dynamics and shrimp growth in an intensive shrimp culture system. The application of STELLA® in animal production is not unusual; it has been used in a several studies (Beukes et al., 2002; Diaz-Solis et al., 2009, 2006, 2003; Gillet et al., 2002; Glasscock et al., 2005 and Sikhalazo, 2005). Diaz-Solis et al. (2003) used STELLA to develop a model that simulated forage production, range condition, diet selection in a beef cow-calf production in Texas rangelands whereas Teague et al. (2008) used it to simulate an ecological economic model for assessing fire and grazing management effects on mesquite rangelands in Texas. In another study

Teague et al. (2009) used STELLA to study the economic implications of maintaining rangeland ecosystem health in a semi-arid savanna. Fellman et al. (2008) used it to estimate the amount of carbon sequestered in soils via livestock waste. In this study a model was developed and the inputs variables of the model were obtained from both the existing literature and from a longitudinal study that involved collection of data from 18 farms for over a period of two and half years.

1.5 Outline of the thesis

The thesis is made of 6 chapters; **Chapter I** presents the general introduction. **Chapter II** gives the results from a field survey undertaken to characterize pasture utilization and management in Ankole pastoral system. It aimed at understanding how livestock keepers manage their rangelands, identify the most important pasture species and overall quality of the rangeland as perceived by the livestock keepers and compare it with the laboratory analysis. This paper is at the final stage of revision and is set according to the Journal, Grass and Forage science. **Chapter III** presents results on the simple method of simulating stochastic rainfall and discusses the pasture dynamics, stocking density and long term carrying capacity of the Ankole pastoral production system. This paper was published in the journal of Livestock Research for Rural Development. **Chapter IV** presents the details of a developed stochastic dynamic simulation model, its parameterization and evaluation. It is set according to the journal, Ecological modeling. **Chapter V** present results on the evaluation of alternative management options using the stochastic model developed and discussed in chapter IV. **Chapter VI** entails the general discussion and summary of the study.

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CHAPTER II

Pasture use and management strategies in the Ankole pastoral system in Uganda

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Abstract

The Bahima ethnic group of South Western Uganda formerly kept exclusively Ankole cattle but has recently begun crossbreeding pure Ankole cattle with Holstein Friesian. Separate herds consisting of pure Ankole and crossbred animals are common. A study was carried out to characterize pasture utilization and management in this rain fed extensive dairy production area to generate information that will assist in the designing of alternative strategies/technology options. The pastoralists were largely carrying out continuous grazing though there is an effort to establish paddocks. *Hyparrhenia rufa*, *Brachiaria spp*, *Themeda triandra* and *Chloris gayana* were identified as the most important pasture species whereas *Sporobolus pyramidalis* and *Cymbopogon afronardus* were the most unwanted plant species. Presence of high quality feed (80%), limited shrubs/weeds (80%) and close proximity to the homestead (30%) were the main factors considered when allocating cattle genotypes to their respective grazing landscapes. Crossbred cattle were kept on medium or high quality pastures whereas Ankole cattle were mostly kept on medium and low quality pastures. Crossbred pasture had 0.17t/ha DM more than the range grazed by pure Ankole cattle. The CP content in pastures grazed by pure Ankole (6.30%) was significantly ($P<0.05$) lower compared to Ankole-Friesian crossbred grazed range (7.25%). NDF content was relatively similar (72.82% vs. 69.77%) in both range types. The perceptions and interpretation of farmers about indicator plant species occurring in the range was important for the selection of pastures for either cattle genotype. The presence of *Brachiaria spp* in the range offers an opportunity for utilization as hay for feeding as supplement during dry season.

Keywords: Ankole cattle, Indigenous knowledge, pastoralists, pasture management, Uganda

2.1 Introduction

In large parts of Africa, livestock production systems in semi-arid areas are generally based on the conversion of pasture into milk and meat by grazing cows (Abdalla et al., 1999 and Sottie et al., 2009) without any supplementation. Livestock production

by the Bahima ethnic group in South Western Uganda is not exceptional. The Bahima were formerly known for keeping exclusively the long-horned Ankole cattle but recent studies (Alary et al., 2007; Serunkuuma, 1998 and Wurzinger et al., 2008) reported that Ankole cattle keepers have begun crossbreeding pure Ankole cattle with Holstein Friesian. Separate herds consisting of pure Ankole and crossbred animals are common. Previous studies (Wang *et al.*, 1992 and Grimaud et al., 2007) reported a positive contribution to milk production when Ankole cattle were crossbred with Holstein–Friesian. However, the introduction of *bos Taurus* breeds in the tropics is limited by a number of problems caused by nutrition and environmental factors (Komwihangilo et al., 2009; Igono and Aliu, 1982; and Matias, 1998). The quantities and qualities of pasture are a big challenge because of the critical shortage of feeds especially during dry season. Before the introduction of crossbreds, livestock keepers coped with pasture deficit mainly by transferring their animals to areas outside the villages where there is plenty of grazing land and possibly more pastures (Mulindwa et al., 2009). However, unlike pure Ankole cattle, crossbreds are unable to trek long distances thereby becoming more vulnerable in events of drought. In hot climates, high ambient temperatures, high direct and indirect solar radiation, lack of air movement and humidity are the main sources of environmental factors that impose strains on animals. These result in a decline in production, such as weight loss or infertility (Finch, 1984). In light of the above, there is need to understand how these pastoralists are coping with the challenges related to pasture management and use given the current shift in their cattle breeding strategy. In the recent past, traditional range management has received some attention (Kyagaba, 2004 and Mapinduzi et al., 2003) because management of rangelands in East Africa is to a large extent dependant on pastoralists' indigenous knowledge of the area. Understanding the indigenous ecological knowledge of pastoralists will complement the designing and implementation of sustainable development programmes aimed at benefiting vulnerable people in the emerging production system in Ankole sub-region. This paper reports on a study that was part of a 3-year multidisciplinary project carried out in south western Uganda. The objective of the study was to characterize pasture utilization and management in a rain fed extensive dairy production area in

order to generate information that will assist in the designing of strategies/technology options that will contribute to comprehensive livestock development programmes.

2.2 Materials and Methods

2.2.1 Study area

The study was carried out in Kiruhura district, south-western Uganda where the landscape is characterised by undulating plains in some and sloping to moderately steep topography in other areas. Mulindwa et al. (2009) computed the mean annual rainfall for the Mbarara Meteorological site at Kakoba for the period 1963 -2008 and obtained a figure of 931 mm with a coefficient of variation of 16%. The rainfall is bimodal peaking in April-May and September to November, with two prolonged dry seasons in June to August and December to February. Temperatures are moderate and equable, with a peak of 29°C with a variation of 2 to 7°C. The animals are managed in such a way that two genotypes (Ankole and Ankole-Friesian crosses) are kept on the same farm but separately grazed on pasture throughout the year.

2.1.2 Survey

The survey was performed on ten selected farms keeping two herds of cattle, Ankole and Ankole-Friesian crossbreds separately. Data was obtained by interviewing pastoralists using pre-tested structured questionnaires between March and June 2008. The interviews were conducted in the vernacular Runyakole language by trained enumerators. Among others the questionnaire contained questions about pasture yield, pasture quality, paddock size of plots from which herbage samples were taken, reasons for allocating a given cattle breed to a specific grazing area, pasture composition, pasture use and management as well as soil erosion status. The information on paddock size is based on farmers' responses; we did not physically measure it. Pasture assessment was done by asking farmers to give a percentage estimate of the proportion of their grazing land that is occupied by low, medium and high yielding pasture. A similar method was used for assessing the quality of pasture. Thorough explanations were given to farmers about the meaning of

pasture quality and quantity because it often happened that they confused the two parameters.

2.2.3 Herbage sampling and measurements

Pasture samples were taken twice. The first sampling was done during late dry season and the second during wet season. The interval between sampling visits was 7 weeks. One paddock was selected from each of the cattle genotype grazing areas at each farm. Only paddocks that had not been grazed for a while were selected and areas near watering points or cattle handling facilities were avoided. On the selected paddock, a method described by Gaucherand and Lavorel (2007) was used to establish two 10m long transect lines, indicated by posts and string. Two transects were performed on every paddock resulting in 4 transects per farm. During the first visit, two pasture samples were taken parallel to the transect line, one sample taken from either side of each transect line. On the second visit samples were taken perpendicular to the each transect line. Transect lines used during the first visit were also used during the second visit. Distances of sampling sites from transect lines varied. The sampled areas were equivalent to 1m² (0.2m x 5m) in size and were marked with four wooden posts and string indicating boundary lines. All herbage enclosed was harvested to ground level using an electric clipper. Fresh weight measurements of the cut pasture were taken and recorded in the field using a pocket balance. After weighing, samples for a given transect were pooled, thoroughly mixed and approximately 0.5kg were taken for further laboratory analysis. Two samples were analysed per genotype per farm. Samples were oven dried for 48 hours at 65°C to obtain dry matter (DM) yield per hectare. Further analysis for crude protein (CP), Neutral detergent fibre (NDF) and Gross energy (GE) was done. Mean gross energy per hectare with respect to genotype and season were obtained by multiplying mean dry matter (t/ha) by GE (MJ/kg). Crude protein concentration was calculated from the nitrogen (N) concentration in the herbage ($N \times 6.25$), determined by the Kjeldahl procedure (AOAC, 1990), NDF was determined using the procedure developed by Van Soest (1963) while Gross energy was determined using bomb calorimeter. Gross energy was analysed using pasture samples from one farm.

2.2.4 Data analysis

The survey data were processed into frequencies and percentage using Microsoft Excel spreadsheet. Data on DMY, CP, GE and NDF were analysed using the general linear model of SAS (2002) in which pasture type, season and farm were included as fixed effects. The farm effect was not considered when analysing GE.

2.3 Results and Discussion

2.3.1 Paddocking

The number of paddocks per farm varied from 1 to 10 paddocks. Five farms had 1 or 2 paddocks. Four farms had more than 2 paddocks and only 1 farm was fully paddocked (10 paddocks). None of the farms had paddocks in the pure Ankole grazing area; paddocks existed only in crossbred grazed pastures. A study by Wurzinger et al. (2008) in this area reported that herds are always accompanied by herdsman who herd them to the grazing area and watering points, a fact that could explain the limited use of paddocks in this system. Despite the reported changes in the system from nomadic to sedentary, communal to individual ownership of land and crossbreeding, results in this study indicate that the system is in a transition where both traditional practices and commercial cattle management methods are being used concurrently. Little investment has been done towards development of paddocks in this area. Rotating animals using herdsman is becoming more difficult as farmers are already complaining of scarce labour. There is need to encourage more use of well planned paddocks as these will ensure efficient grazing of pasture and small labour force. Studies done elsewhere (Corsi et al., 2000) reported an increased stocking rate from 0.8 to 1.2TLU/ha/year, mainly due to better grazing efficiency associated with rotational grazing using paddocks.

2.3.2 Soil erosion

Presence of soil erosion signs is used to determine the existence of overgrazing in a rangeland. Out of the 20 pasture paddocks assessed; only 4 were described as

having signs of soil erosion. Based on farmers' responses, no crossbred pastures were indicated to having soil erosion signs whereas 40% of Ankole pastures were described as being affected by erosion. Two farmers reported that the state of soil erosion on their farms has remained static whereas 2 farmers were not in position to indicate a trend. Given the fact that Ankole cattle are kept on areas with less herbage yield and low quality forage, they (Ankole) seem to carry out intensive selective grazing targeting the limited good quality pasture species thereby exposing the ground. The difference between farms in regards to soil erosion presence could be attributed to variation of stocking density. Mulindwa *et al.* (2009) reported that 63% of surveyed farms in this study area had stocking densities that were higher than carrying capacities throughout the year while 37% overstock during dry months. Villamil *et al.* (1997) noted that inappropriate cattle grazing practices, such as overgrazing harm the quality of natural pastures and soil properties. Overgrazing adversely effects soil properties such as reduced infiltration and accelerated runoff leading to soil erosion. The findings call for measures aimed at mitigating water erosion, first by raising an appropriate number of animals per unit area. Estimation of carrying capacity for each of the production month of the year would give a clear indication and range of stocking rates within which pastoralists could operate and also make decisions on when to reduce the animal numbers or supplement with other feed resources.

2.3.3 Pasture utilisation

The results on criteria used by farmers to allocate grazing areas to the respective cattle genotypes on a particular farm are presented in Table 1. The most important factors considered when allocating grazing land for crossbred cattle were: availability of high quality feed (80%) and limited shrubs/weeds (80%), followed by close proximity to the homestead (30%). Ankole cattle were largely grazed on areas infested with shrubs (50%), areas farmers considered to be dominated by pasture species of low quality and areas that are further away from watering points (30%). The majority of farmers (8) were keeping cattle on pastures without any rotation grazing. 9 farmers that kept Ankole cattle permanently on the same pasture 7 for

crossbred cattle. On 1 farm, crossbred cattle were grazed under a rotational grazing system with one week of grazing and 9 weeks resting period per paddock. This farm was a special case as it had 10 fenced paddocks for the crossbred herd and conserved forage in form of hay. With the exception of 1 farmer, all farmers reported that they would keep exclusively cattle genotype separated on selected pastures. 1 farmer did not have a definite response in regard to utilising the same grazing land for both genotypes or grazing them separately. Bush clearing was the major pasture improvement method used on all farms. Additionally unpalatable plants, like lemongrass (*Cymbopogon afronardus*), were being cleared mainly from pastures grazed by crossbreds. These findings indicate that farmers give preferential treatment to crossbred herds. They stressed that unlike pure Ankole cattle, crossbreds grazed in bushy pastures tend to suffer from eye infections as well as frequent non-infectious abortions caused by grazing on poisonous weeds. Armed with lifelong experience with Ankole cattle, farmers are in the position of making informed decisions. For example crossbred cattle can hardly walk very long distances hence the decision to keep them near homesteads and watering points. The farmers' decisions are backed by previous studies in this area (Okello and Sabiiti, 2005; Serunkuuma and Oslon, 1998) that argued that Ankole cattle have high adaptability to harsh conditions prevailing in Uganda rangelands and are capable of trekking long distances.

Table 2.1: Factors considered by farmers when allocating grazing land to the respective cattle genotype

Factor	Crossbred pastures (n=10)	Ankole pastures (n=10)
Readily available water	2	0
Water not readily available	0	3
High quality feed	8	1
Minor quality feed	0	6
Limited shrubs and weeds	8	0
Infested with shrubs	0	5
Close proximity to homestead	3	0
Distant from homestead	0	1
Dairy animals	1	0

2.3.4 Pasture species composition, their quality and trends

Dominant plant species considered as "good" and "bad", and their respective qualities are presented in Table 2 and 3. *Hyparrhenia rufa* (8) (number in brackets indicates the frequency a given species was mentioned) and *Brachiaria sp* (8) were ranked as the most important pasture species followed by *Themeda triandra* and *Chloris gayana*. *Sporobolus pyramidalis* was ranked as the worst species followed by *Cymbopogon afronardus*. Most common attributes of "good" plant species were: high nutrient content and high herbage yield. *Hyparrhenia rufa* was mentioned to have the additional attribute of being highly resistant to drought unlike *Brachiaria sp* and *Themeda triandra*. The latter was reported to sprout very fast at the onset of rains. Given the qualities farmers attributed to each species, these species offer an opportunity of temporal utilisation for feeding cattle at different times of the year. *Brachiaria spp* could be harvested during rainy season, conserved in form of hay and fed to cattle as a supplement to *Hyparrhenia rufa* during dry season. The current study did not investigate the prevalence of the above pasture species but an earlier study by Byenkya (2004) in this area showed that *Brachiaria spp.* were most prevalent accounting for 34% of basal cover of all grasses followed by *Hyparrhenia spp.* (12%).

When asked about the history of species composition and trends of the most common plant species, 70% of farmers acknowledged that certain plants have been gradually disappearing from their rangelands during the last 10 years while 30% did not notice disappearance of any pasture species. The pasture species noted as gradually reducing in quantity were *Hyparrhenia rufa* (5), *Chloris gayana* (2) and *Brachiaria sp* (1). Species noticed to be gradually increasing over the last 10 years were *Sporobolus pyramidalis* (4), *Lantana camara* (3) and *Cymbopogon afronardus* was mentioned by 1 farmer. Farmers' observations are supported by earlier findings by Harrington and Pratchett (1973) who observed a frequency presence for *Sporobolus pyramidalis* of only 7% in a valley bottom paddock ranking it among the least prevalent out of the 19 species encountered whereas Byenkya (2004) reported a frequency of occurrence of *Sporobolus pyramidalis* of 20%. It is also important to note

that species mentioned as gradually reducing over time belong to the category "good" whereas those observed to be increasing belong to the category "bad". This could possibly be due to the fact that when grazing, animals tend to select the most palatable species leaving unwanted species in the range. Therefore "bad" species are not subjected to intensive stress caused by grazing (defoliation) and over time out-compete "good" species.

Table 2.2: Plants considered “good” and their respective qualities

Plant (times mentioned)		
Local name	Botanical name	Qualities described (times mentioned)
Emburara (8)	<i>Hyparrhenia rufa</i>	Highly nutritious (6) Increases milk production (2) Drought resistant (3) Cows produce concentrated milk (1) Fattens animals (1) Palatable (1)
Ekijubwe (8)	<i>Brachiaria sp.</i>	Highly nutritious (6) Increases milk production (2) Animals grow fat and are healthy (1) Soft (1) High herbage yield (1) Very palatable (1) Not drought resistant (1)
Orunyankokole (3)	<i>Chloris gayana</i>	Highly nutritious (1) Nitrogen source (1) Fattens animals (1) Increases milk production (1) Rare plant (1)
Kyooya (1)	<i>n.s.</i>	Soft plant (1)
Ekikamba (1)	<i>n.s.</i>	Nitrogen source (1)
Marende (1)	<i>n.s.</i>	Nutritious (1)
Eyojwa (4)	<i>Themeda triandra</i>	Nutritious (3) Drought resistant (2) Not drought resistant (1) Sprouts very fast after rain (1) Animals like it especially at rest (1)
Orukwamba (1)	<i>Cynodon sp.</i>	
Eyojo (1)	<i>n.s.</i>	Animals fatten (1) Increases milk production (1)

Numbers in bracket indicate the frequency a given species was mentioned

Table 2.3: Plants considered “bad” and their qualities

Plant species		
Local name	Botanical name	Qualities
Egashi (10)	<i>Sporobolus pyramidalis</i>	Causes loss of cattle's teeth (8)
		Hard to chew (5)
		Neck meat becomes harder (1)
		Out competes other species (1)
Omutete (6)	<i>Cymbopogon afronardus</i>	Sharp edges injure cow's lips/mouths (2)
		Out competes other species (2)
		Hideout for ticks and tsetse flies (1)
Ekicuguza-Mbogo (2)	<i>n.s.</i>	Causes diarrhoea (1)
Ekihuki (1)	<i>Lantana camara</i>	Poisonous (1)
		Causes photosensitivity (1)
Kagyenz'enda (1)	<i>n.s.</i>	Thorny plant (1)
Eyojwa (1)	<i>Themeda triandra</i>	
Marende (1)	<i>n.s.</i>	Causes diarrhoea (1)

Numbers in bracket indicate the frequency a given species was mentioned

2.3.5 Comparison of farmers' rangeland quality grading and laboratory pasture assessment for CP, NDF and GE analysis

Results of farmers' assessment of rangelands in regard to quality and laboratory analysis are presented in Table 4. Three farmers graded their farm pastures into high and low quality, 3 farmers graded it into medium and high quality, 2 farmers graded their pastures into low and medium quality and 2 farmers graded their rangeland into all three categories. Crossbred cattle pastures were graded into medium (5) or high (5) quality while Ankole cattle grazed pastures were graded into medium (6) and low (3) quality with only 1 farm having a high quality grade pasture for Ankole. No crossbred range was evaluated to have low quality pasture. Results from laboratory

analysis show that CP and NDF values for farms ranged from 5.56% to 8.51% and 68.24% to 81.60% respectively. CP content between pastures grazed by different genotypes was significantly ($P<0.05$) different (Table 5). Crossbred grazed pasture had 3211MJ/ha more gross energy than Ankole grazed pasture. Laboratory analysis showed also that crossbred pastures had on average CP and NDF of 7.25% and 69.77% while Ankole pastures had 6.30% and 72.82% respectively. NDF content was slightly higher on crossbred range 72.82% compared to 69.77% on Ankole range though both figures were higher than those (63 and 62%) reported by Mugasi et al. (2000) who also claimed that high crude fiber level is common in tropical pastures attributed to high temperatures which lead to lignification. Forage NDF is an index of how much forage livestock will eat. As NDF increases, forage intake decreases (Van Soest, 1965) and when forage availability does not limit intake, NDF may be the intake-limiting factor in pastures. In addition, appetite is depressed and pasture intake is lower than expected (Minson, 1982; Forbes, 1986) if crude protein levels are below the limiting range of 6-8%. There is a general agreement between farmers' quality assessment and the laboratory analysis. For farms (numbers 4, 8, and 10) that had pasture graded into medium and high quality categories, laboratory analysis showed that these pastures had high crude protein contents (7.40, 6.43 and 6.29) and relatively low NDF (68.96, 69.75 and 69.34). Farms graded into low and medium categories (6 and 7) had lower CP (6.72 and 5.56%) and relatively high NDF (72.07 and 72.94). However, the CP figures reported in this study are generally lower than those reported by Mugasi et al, (2000), 9.15% on cleared farms and 8.92% on bushy farms. The high CP content found in crossbred grazed pastures and their being highly rated by farmers is explained by the fact that they contained more legume species than pastures grazed by pure Ankole cattle as reported by Roschinsky (2009).

Table 2.4: Comparison of farmers' rangeland grading (Quality) and CP (%) and NDF with respect to farm

Farm	Quality assessment (%)			Laboratory assessment	
	Low	Medium	High	CP (%)	NDF (%)
1	50	0	50	5.56	72.94
2	10	0	90	6.29	69.34
3	15	0	85	8.51	68.24
4	0	20	80	7.40	68.96
5	10	20	70	7.50	81.60
6	50	50	0	6.72	72.07
7	20	60	20	7.85	69.07
8	0	10	90	6.43	69.75
9	35	65	0	5.56	72.94
10	0	10	90	6.29	69.34
se				0.66	4.18

Table 2.5: Comparison of Farmers' rangeland grading (quality) and CP NDF and GE with respect to breed

Breed	Farmers grading quality (n=20)			Laboratory analysis		
	Low	Medium	High	CP (%)	NDF (%)	GE (MJ/ha)
Crossbred	0	5	5	7.25 ^a	69.77	35121
Ankole	3	6	1	6.30 ^b	72.82	32810
Se				0.28	1.79	

Superscripts ^a and ^b indicate significant difference, (P <0.05)

2.3.6 Comparison of farmers' rangeland quantity grading and laboratory pasture assessment for DMY analysis

Results on farmers' assessment of rangelands in regard to quantity and laboratory analysis are presented in Table 6. In regard to herbage yield (quantity), 3 farmers graded their range into low and high, 3 into medium and high, 2 into low and medium and 2 into all three categories. When asked to give percentages constituting the mentioned grades, results show that both high and medium yielding received the highest percentages while low yielding received the lowest. Although not clear cut, farms (8 and 10) graded into medium and high were also found to have higher DMY (2.23 and 2.49 t/ha) compared to farms (6 and 9) graded into low and medium (1.88 and 1.99 t/ha). Both assessments (laboratory and farmers') indicate that there is a variation between farms in terms of DMY which could be attributed to differences in pasture management and stocking rates.

When grading is categorized based on genotype (Ankole vs. crossbred), 5 farmers graded rangeland grazed by crossbreds into medium and 5 into high quantity (Table 7). Ankole rangelands were graded into low, medium and high quantity by 3, 6 and 1 farmers respectively. A general relationship appears to exist between quality and quantity grading whereby species considered by farmers to be of high quality also produce high herbage yields. Dry matter yield laboratory analysis showed a significant ($P < 0.05$) difference between pastures grazed by different genotypes. Ankole-Friesian crossbreds grazed pastures with 0.17t/ha more dry matter than pure Ankole grazed pastures. As observed from criteria used by pastoralists to allocate grazing land, these findings confirm the fact that farmers allocate areas with good pastures to crossbreds whereas pure Ankole is grazed on poor pastures. None of the farmers graded crossbreed grazed pasture as low quantity. Personal observations conform to the estimates given by the farmers. The figure of 1.96t/ha DM in Ankole grazed pasture is rather misleading as these areas were mainly dominated by *Sporobolus pyramidalis* and *Cymbopogon afronardus*, species that were referred to by pastoralist as less palatable. It is believed that pastoralists compensate pure Ankole cattle herds by allocating them to a larger percentage of grazing area compared to crossbreds. Additionally Ankole cattle fulfill their DMI demands by

selective grazing. A study by Galukande et al. (2008) showed that body condition score for Ankole and Ankole-Friesian crossbreds did not differ significantly whereas Okello et al. (2005) reported that despite poor conditions in dry spells, Ankole cows maintained a constant body condition score over the year. They claimed that that performance evidences Ankole cattle's adaptation to harsh climatic conditions prevailing in the region, which was partially attributed to their ability to select richer forages.

Table 2.6: Comparison of farmers' rangeland grading (yield) and DMY (t/ha) per farm

Farm	Pasture yield assessment (%)			DMY (t/ha)
	Low	Medium	High	
1	66	0	34	2.49 ^a
2	10	0	90	2.25 ^a
3	5	0	95	1.63 ^b
4	0	20	80	1.78 ^b
5	25	35	40	2.01 ^{ab}
6	60	40	0	1.88 ^b
7	30	20	50	1.90 ^b
8	0	10	90	2.23 ^a
9	35	65	0	1.99 ^b
10	0	10	90	2.49 ^a

Superscripts ^a and ^b indicate significant differences, (P<0.05)

Table 2.7: Comparison of Farmers' rangeland grazing (yield) and DMY with respect to breed

Breed	Pasture yield (n=20)			DMY (kg/ha)
	Low	Medium	High	
Crossbred	0	50	50	2.13 ^b
Ankole	30	60	10	1.96 ^a

Superscripts ^a and ^b indicate significant difference, ($P < 0.05$)

2.3.7 Season effect on DMY, CP, NDF and GE

Least square means of the effect of season on DMY, CP, NDF and GE are presented in Table 8. There was no observed significant ($P > 0.05$) season effect on DMY though at early wet season MD was 0.25t/ha more than at late dry season. Season did not have a significant ($P > 0.05$) influence on crude protein content though late dry season CP (6.96%) was higher than early wet season (6.59%). CP values are higher than 3% reported for both March and June by Okello *et al.* (2005) working on Ankole pastures in the same region. Season and range type interaction was not significant ($P > 0.05$) though late dry season CP was higher in both range types. Neutral detergent fibre was not significantly ($P > 0.05$) influenced by seasonal effect but a previous study (Kagoda, 2001) found that NDF of pastures in south-western Uganda varied according to seasons. Although not significant, dry season NDF content was higher than that of wet season a scenario that agrees with findings (73.8% vs. 64.1%) reported by Kagoda (2001). In a study by Okello *et al.* (2005), it was reported that NDF in herbage was relatively high throughout most of the year, accounting for between 760 and 840g per kg dry matter, with low seasonal fluctuation. The high NDF values for dry season in this study could be attributed to course of maturation of forage whereby it tends to lignify.

Table 2.8: Seasonal effect on dry matter yield, crude protein and NDF

Season	Quality parameter				
	N	DMY	CP	NDF	GE
Late dry	38	1.97	6.96	73.40	32813
Early wet	36	2.12	6.59	69.19	35311
Stderr		0.10	0.29	1.81	

2.4 Conclusion and recommendations

This study aimed at generating information about farmers' awareness of the state of their range and how they have applied their indigenous knowledge to the utilisation of their rangelands. The study has revealed that farmers perception and interpretation of indicator plant species was important for allocation of pastures to cattle genotype. Medium or high quality graded areas were allocated to crossbred cattle. Although subjective, farmer's assessment of their pasture in terms of quality and quantity concurred with laboratory analysis. These livestock keepers possess immense knowledge about traditional forage species which they ably identified and hence there is a need to involve them in the promotion of fodder production. The most important plant species as identified by farmers were *Hyparrhenia rufa*, *Brachiaria spp*, *Themeda triandra* and *Chloris gayana*. The most common unwanted species were *Sporobolus pyramidalis* and *Cymbopogon afronardus*. Possibly the greatest obstacle to improving Ankole pastures is the low priority farmers place on pasture concerns relative to livestock husbandry. Apart from clearing weeds, there is limited effort towards proper use of the rangeland. We recommend that any pasture development program should focus on those species that are adapted to the area and which farmers are familiar with and have confidence in. Given its quick growth response to rains, high herbage yield, and susceptibility to drought, *Brachiaria spp* could be utilized for making hay to be fed as supplement during dry season. One of the first steps of introducing new technologies on these farms should be the use of rotational grazing using small sized paddocks which allow the pasture to be more efficiently grazed.

Acknowledgement

The authors acknowledge the Government of Austria for financial support through Austrian Development Agency.

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CHAPTER III

Modelling of long term pasture production and estimation of carrying capacity of Ankole pastoral production system in South Western Uganda

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Abstract

The Ankole pastoral production system in South Western Uganda is based on grazing without supplementary feeding. A stochastic simulation model was developed to determine the dynamics of pastures grazed by Ankole cattle and their Holstein Friesian crosses and the carrying capacity (CC) of the livestock grazing system. The model used the concept of rain use efficiency which relates pasture production to rainfall. A cross sectional study was carried out on 16 selected farms and data on number of animals, sex, age group and size of available grazing land was collected. The similarity between the results of the simulation rainfall runs and field data are considered to be satisfactory. The overall annual forage production is $3905 \pm 72 \text{ kg/ha}$. The lowest CC (5.65 ± 0.75) occurs in long dry season (June to August) while the highest CC ($1.41 \pm 0.06 \text{ ha/TLU}$) occurs in short rain season (September to November). Annual carrying capacity ranges between 1.88 and 2.08 ha/TLU with an overall mean of $1.95 \pm 0.04 \text{ ha/TLU}$. Sixty three (63%) percent of the surveyed farms have stocking rates that are higher than the CC throughout the year while the rest are overstocked in the dry seasons of the year. The results indicate that CC is dynamic and its variability is more pronounced within the year than between years. In response to seasonal CC, the major point of intervention in regard to reduction of actual stocking rates could be done in May shortly before the start of the long dry season. For Ankole pastoral system to be sustainable, the stocking rate should not go below 1.41 ha/TLU.

Key words: Rain use efficiency, rangelands, simulation, stocking rate

3.1 Introduction

The Ankole cattle production system in South Western Uganda is based on grazing without supplementary feeding. In this area livestock production is highly dependent on the availability of pastures, the quantity and quality of which are primarily determined by the amount and distribution of rainfall. This rainfall pattern formerly forced cattle keepers to move their cattle from place to place in search of water and pastures. However, the system is undergoing transformation from nomadic to sedentary system due to a new national policy that allows change of land tenure from communal to private rangeland tenure (Sserunkuuma and Olso 1998; Kisamba et al.,

2006). Another on-going trend is the practice whereby pastoralists raise two separate herds on the same land, a crossbred Ankole-Holstein Friesian herd for commercial milk production and pure Ankole as a risk management strategy, in order to enhance the productivity of their herds. This practice results in high stocking densities and higher likelihood of overgrazing. In a study by Sserunkuuma and Olso (1998) in South Western Uganda, the authors concluded that any program aimed at enhancing range productivity and mitigating overgrazing should attach as much weight to feeding and animal health care, as it does to breed improvement. A wide variation in pasture quality and quantity, as well as cow performance was observed between seasons (Okello et al., 2005). The success of the current grazing strategy will therefore depend on the ability to track forage availability on the range and matching it to the number of animals that can be grazed on the rangeland. The amount of available forage and the number of animals grazing on an area affect intake and therefore animal nutritional performance, productivity per unit area and the long term ecological health of the rangeland.

The close relation between annual rainfall and rangeland productivity is widely acknowledged (Coe et al., 1976; De Leeuw and Nyambaka 1987). As water is the main limiting factor in most rangelands, high and well distributed rainfall will result in increased productivity. Climate variables, especially rainfall in semiarid and arid areas, have overriding effects on grassland production, and thus affect livestock carrying capacity (Mei et al., 2004). Carrying capacity refers to the total number of animals that may be safely supported by a unit rangeland in the long term (Caltabiano 2006). A predictive model for carrying capacity, determined directly from rainfall, was established by Coe et al. (1976) based on data obtained mainly from natural ecosystems in Africa. Oosterheld et al (1992) developed separate regression models between aboveground net primary production and herbivore biomass for wildlife and livestock based on data from South America. Carrying capacity, or the ability of a given area to support a certain population of animals on a continuing basis (De Vos 1969) may be altered by both long and short term variations in climate and particularly in precipitation (Phillipson 1975). The objective of this study was to develop a computer simulation model to predict the dynamics of herbage productivity

of the range grazed by Ankole cattle and crosses with Holstein Friesian and to determine the carrying capacity of the rangeland.

3.2 Materials and Methods

3.2.2 The study area

The study was carried out in Mbarara district of South Western Uganda. The topography consists of undulating hills and valleys. The hills rise about 100–200m above the flat valley bottoms. The area lies 1250–1525m above sea level. Rainfall has in the past been reliable, but recent trends in rainfall patterns indicate more erratic behavior. The rainfall occurs in a bimodal pattern, peaking in the months of April to May and September to November. The current study used historical rainfall data for 46 years and obtained an annual rainfall mean of 939mm. The months of June, July and August normally constitute a dry season with very little rainfall. Schwartz et al. (1996) have computed the mean annual rainfall for the Mbarara Meteorological site at Kakoba for the period 1980 -1994 and obtained a figure of 882 mm with a coefficient of variation of 20%. Mean maximum temperature is about 26° C and mean minimum around 14° C. *Themeda triandra*, *Cynodon dactylon*, *Panicum maximum*, *Brachiaria decumbens*, *B. platynota* and *Chloris gayana* are quantitatively the most valuable forage grasses for cattle. *Hyparrhenia filipendula*, *Loudentia kagerensis*, *Digitaria maitlandi* and to a small extent, *Sporobolus pyramidalis*, are less important due to their lower quality, but form a major component of the grass vegetation (Okello et al., 2005).

3.2.3 Model description

A dynamic stochastic compartment model based on difference equations programmed in STELLA 9.0.2, 2007 (High Performance Systems, Inc., Hanover, New Hampshire,) was developed. The simulations are based on a one-month time step (i.e units of the model are in months). Due to the stochastic nature of the model, results of the simulation are presented as means for 50 separate runs of the model. The main assumption in the model is that vegetation growth is directly related to the rainfall dynamics. The model simulates the dynamics of standing green forage using the

concept of rain use efficiency (RUE, kg DM/ha/mm/year). The RUE factor, which refers to a relationship between maximum standing crop at the end of a rainy season, and total annual rainfall (mm), was used to calculate the carrying capacity of Ankole pastoral system. Le Hou  rou et al. (1988) reported a $RUE = 4.0 \pm 0.3$ for range type, condition and productivity for areas with similar conditions to those of Ankole pastoral production system. In order to simulate the observed seasonal variation in forage production, monthly rainfall is generated randomly from a cumulative relative frequency distribution (Grant et al., 1997) for each month, created from real system historical rain fall data of 46 years (from 1961 to 2007) obtained from the Kakoba Metrological Department, Mbarara.

Equation 1

$MRF = \text{RANDOM}(\text{Cumulative relative frequency})$

Where, MRF is the monthly rainfall (mm) and cumulative relative frequency is a value picked randomly from 0-1.

Random is a built-in function in STELLA that generates a series of uniformly distributed random numbers between 0 and 1 for each month and samples a new random number in each iteration of a model run. Each randomly picked number has got a corresponding amount of rainfall depending on the month (January to December) being simulated. Pasture growth is simulated in monthly time steps using a multiplicative function of rain use efficiency and monthly rainfall. Seasonal forage growth was obtained by summation of forage growth that occurred during the months that constitute a particular season. The four seasons considered were short dry season (December-February), long rain season (March to May), long dry season (June to August) and the short rain season (September to November). The model input data required, consisted of climate and intake of tropical livestock unit (TLU). One Tropical livestock unit represents a ruminant of 250kg live weight (Sserunkuuma and Olson 1998). Annual rainfall is modeled as the summation of the individual monthly rainfall within a given year.

$GR = RUE * MRF$, where GR is the monthly forage growth (kg DM/month/ha)

A basic technique for determining carrying capacity is to calculate the total amount of forage at the end of the growing season, multiply this by a correction factor and then divide by the average yearly feed requirements of a livestock unit (Hocking and Mattick 1993). Not all range forage can be used by livestock, some is not accessible to the animals and some is unpalatable and further losses occur due to senescence and by trampling by the animals (Hocking and Mattick 1993). In order to account for sustainability a proper use factor was included, which varies according to different researchers and different situations from 30% in Southern Ethiopia (Cossins and Upton 1987) to 45% in Tsavo, Eastern Kenya (Van Wijngaarden 1985). Van Wijngaarden (1985) estimates that not more than 55% of the grass cover should be removed in one way or the other to keep the grasslands at least in the same condition as it was before. So, if utilizing the grasslands should be sustainable, to prevent degradation, at least 45% of the peak standing crop should be left at the beginning of the next rainy season. Other authors, Kavana et al. (2005) and Mugerwa (1992) used a proper use factor of 50% while Caltabiano (2006) proposed a factor of 30% for black spear grass and 20% for mulga pastures. In this study, a year long proper use factor of 30% as used by Guevara et al. (1996) was adopted and used as consumable forage. The model uses the measure of livestock input on the range known as the tropical livestock unit (TLU) to calculate the carrying capacity (CC) of the range. Daily feed intake per TLU was taken at 2.5% of body weight. The following equation for the use of forage production was applied (FAO 1991):

Carrying capacity (CC) = animal requirement / weight of standing crop * proper use factor

A cross sectional study was carried out in April 2006 on 16 selected farms. The observations recorded included number of animals, sex, age group and size of grazing area. All cattle age groups were converted to Tropical Livestock Units (TLU). TLU is used to bring all animal types under a common denominator (using conversion factors: 0.25TLU for calf, 0.5TLU for Ankole heifer, 0.6 for Ankole-Friesian heifer, 1 TLU for Ankole cow and 1.2TLU for Ankole-Friesian cow and 1.5 TLU for bulls

respectively). The detailed equations used in the parameterising of the model are presented in Appendix 1.

3.3 Results and discussion

The similarity between the results of the simulation rainfall runs and field data are considered to be satisfactory (Figure 3). The simulated annual mean rainfall was 976 mm which is comparable to the actual annual mean of 939 mm for the study area. The coefficient of inter-annual variation based on the simulated rainfall values was 2% which is far less than the 16.4% calculated based on historic values. The simulation managed to capture monthly rainfall variability but showed less variation in the annual rainfall and yet annual rainfall was obtained by summing up the monthly rainfall for the individual months. In Table 1, the mean long-term annual forage productivity was predicted to be $3905 \pm 73 \text{ kg/ha}$ over a 30 year period which is close to 3900 kg/ha reported by Mugerwa (1992) and considerably lower than 4560 kg/ha estimated by Byenkya (2004).

In this study, the minimum and maximum forage produced were 3664 kg/ha and 4036 kg/ha respectively. The difference between the current study and previous ones could be due to the fact that earlier studies were based on one-year rainfall whereas the current study is based on 30 year rainfall data. Predictions of dry matter have been overestimations and are often unreliable when made for one particular year (FAO 1991). The overall carrying capacity predicted in this study was $1.95 \pm 0.04 \text{ ha/TLU}$ which is higher than 2.27 ha/TLU (Byenkya 2004) and lower than 1.63 ha/TLU reported by Mugerwa (1992). Hocking and Mattick (1993) reported a carrying capacity in the range of $2.5\text{--}3.5 \text{ ha/LU}$ for wooded grasslands of Tanzania receiving 875–1000 mm of annual rainfall. Carrying capacity variability is more pronounced within year than between years (Tables 1 and Figure 2). The low variability in annual CC could be partly explained by the failure of the model to capture annual rainfall variability as indicated by the low coefficient of variation among the simulated annual rainfall.

The lowest CC (5.65 ± 0.75) occurs in long dry season (June to August) while the highest CC ($1.41 \pm 0.06 \text{ ha/TLU}$) occurs in short rain season (September to November). The dynamic nature and seasonal changes are dramatically visible though the

variability of annual carrying capacity was negligible ranging between 1.88ha/TLU and 2.08ha/TLU. The results show that carrying capacity is a dynamic concept requiring active monitoring and rapid adjustments of stocking rates. The implication of this could be a move towards more flexible and short-term responses to environmental variation. Currently farmers respond to within year changing carrying capacity, especially in the dry season, by transferring pure Ankole herds to distant alternative rangelands or grazing in adjacent unfenced land. However, this practice will soon not be possible because of increased demand for land due to population increase.

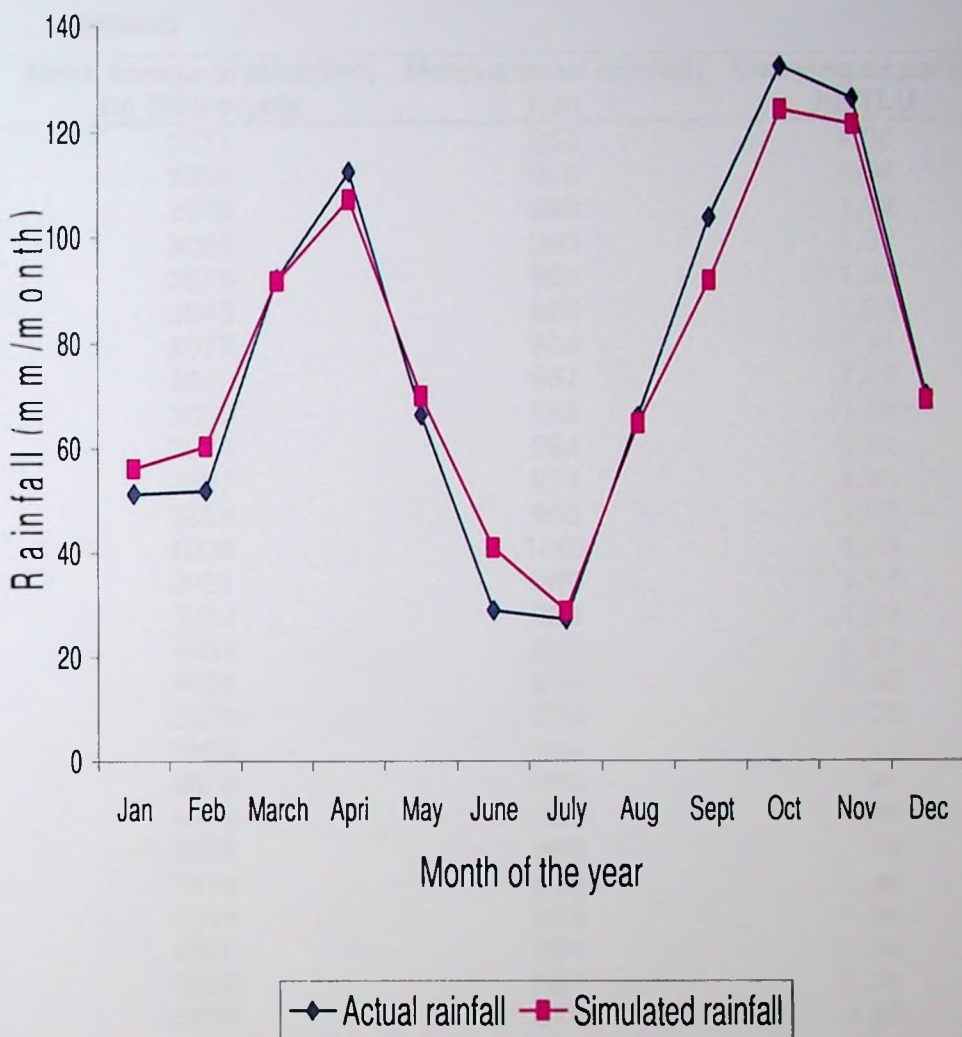
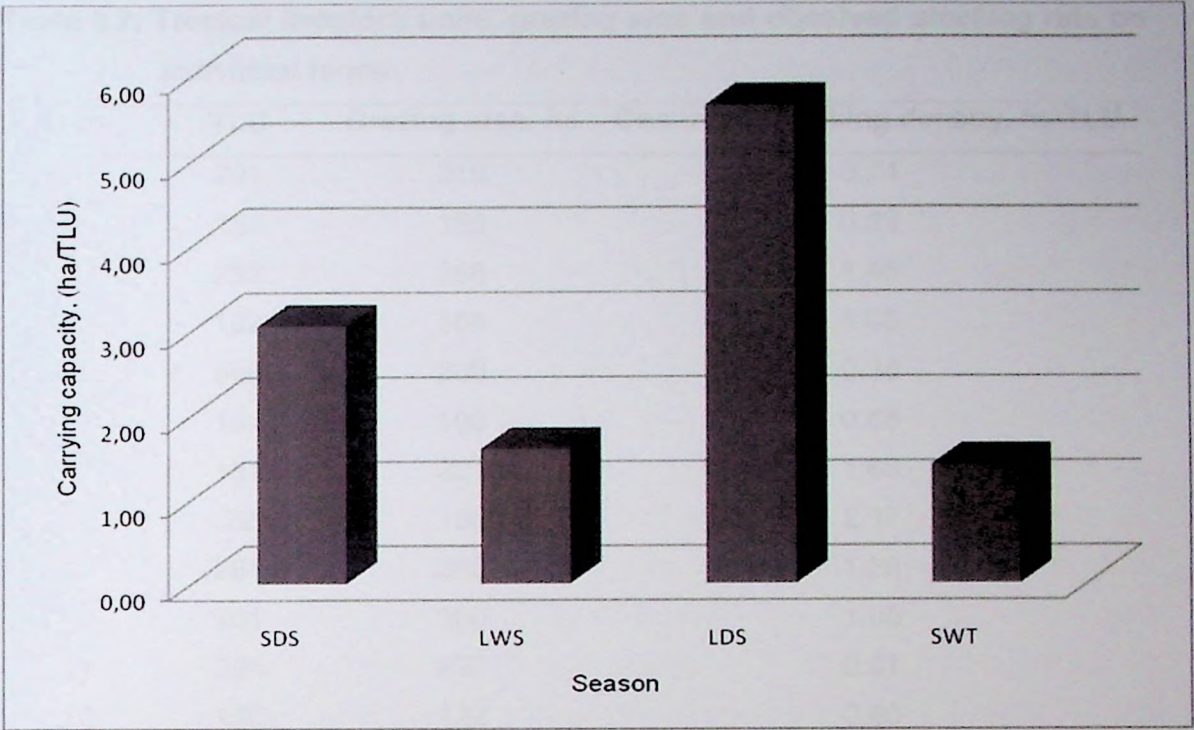


Figure 3.1: Actual and simulated monthly rainfall

Table 3.1: Pasture production, rainfall and carrying capacity in Ankole pastoral system

Year	Mean forage production, Kg DM/ha/year	Mean annual rainfall, mm	Carrying capacity, ha/TLU
1	3811	953	2,00
2	3664	916	2,08
3	3970	992	1,92
4	3865	966	1,97
5	3878	969	1,96
6	3943	986	1,93
7	3977	994	1,91
8	3829	957	1,99
9	3850	962	1,98
10	3974	994	1,91
11	3897	974	1,95
12	3858	965	1,97
13	4036	1009	1,88
14	3921	980	1,94
15	3932	983	1,93
16	3951	988	1,92
17	3902	976	1,95
18	3900	975	1,95
19	3936	984	1,93
20	3876	969	1,96
21	4014	1004	1,89
22	3927	982	1,94
23	3876	969	1,96
24	3849	962	1,98
25	3920	980	1,94
26	3826	957	1,99
27	3886	972	1,96
28	3988	997	1,91
29	3921	980	1,94
30	3977	994	1,91



SDS = Short dry season (December to February), LWS = Long rain season (March to May),
LDS = Long dry season (June to August), SWT = Short rain season (September to November)

Figure 3.2: Mean seasonal carrying capacity

Table 3.2: Tropical livestock units, grazing area and observed stocking rate on individual farms

Farm	TLU	Grazing area, ha	Observed Stocking density, ha/TLU
1	291	215	0.74
2	135	120	0.89
3	252	366	1.45
4	102	108	1.05
5	559	200	0.36
6	151	100	0.66
7	131	221	1.68
8	72	150	2.07
9	281	360	1.28
10	301	300	1.00
11	296	270	0.91
12	152	122	0.80
13	369	750	2.03
14	124	240	1.93
15	218	350	1.60
16	185	220	1.27

Basing on results in figure 2 and Table 2, it is clear that 63% of the surveyed farms have stocking rates that are higher than the CC throughout the year while 37% overstock in the dry months of the year which indicates a risk of overgrazing in this production system. Traditionally, in the study area cattle are a store of wealth or savings from which withdraws are made only for special social occasions or emergency needs hence a reluctance for pastoralists to sell cattle regularly even when faced with forage scarcity.

Although farmers keep stocking rates that are higher than the carrying capacity, it does not necessary mean that animals do not meet their nutrient requirements. The CC obtained in this study was based on dry matter yield without considering nutrient quality of pasture and yet Okello et al. (2005) reported crude protein content of cattle diets that showed a third peak in August (60gkgDM^{-1}) in addition to the May and November peaks (100 and 80gkgDM^{-1} , respectively). Dietary crude protein peaks at the climax of herbage growth and falls in the late wet season (Okello et al., 2005) and through dietary selection as well as increased browsing activity of cattle in the dry season animals are able to meet the $60\text{--}80\text{gkgDM}^{-1}$ crude protein level required for optimal digestion and feed intake (Minson 1981) and hence compensate for low forage crude protein in the dry season and low available forage per TLU caused by high stocking rates. Nevertheless, according to Okello et al. (2005) live weight increased with each rainy season, peaking in May and November, before consistently declining to the lowest levels in the dry seasons. Farmers need to make marginal adjustments to actual stocking rates in response to seasonal carrying capacity and the major point of intervention could be done in May, shortly before the start of long dry season. However, massive reduction in stocking rates, at a specific time of the year, through off-takes could lead to low prices for the sold animals as a result of demand and supply forces. In the short term, stocking rate reductions could be done in two ways namely by off-takes and transferring animals to alternative rangelands. As a long-term strategy, improvement and establishment of marketing infrastructure and institutions such as regular cattle auction houses, slaughter houses and processing meat plants could play a role in keeping the prices stable and encourage

managed off-takes and restocking of animals in response to biological variation of the range carrying capacity.

Government intervention aimed at changing the attitude of farmers through sensitization on the dangers of overstocking could help farmers adopt sustainable stocking rates. The sensitization could be easily integrated in the current on-going national program; national agricultural advisory services (NAADS). The current study has determined the extreme potential carrying capacity values (1.41 and 5.65ha/TLU), there is need to evaluate selected stocking rates that fall within the above range for economic viability and the findings of such a study will provide economically profitable range of stocking rates within a cattle keeper could operate other than recommending a single static CC because a range ensures social interests (keeping larger herds) as well as economic viability with ecological sustainability. Operating within a range of stocking rates will occasionally lead to slight overgrazing in some months causing loss of body weight but the effect will not be severe because cattle will be able to recover in the more favourable months. The practice will also call for supplementation of cattle with hay especially for crossbred animals which demand high quality forage to support their higher milk yield potential and hence a need for a cost benefit analysis study to ascertain the feasibility of supplementation. Retention of fewer but more productive crossbreed animals could be an alternative strategy.

3.4 Conclusions

Carrying capacity (CC) is dynamic and its variability is more pronounced within the year than between years. There is a great disparity between the observed stocking rate and the carrying capacity of the production system. Although big short term changes to stocking rates may not be possible the major point of intervention to reduce stocking rates could be done in May, shortly before the start of long dry season. Based on the results of this study, for the Ankole pastoral system to be sustainable, the stocking rate should not go below 1.41ha/TLU.

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CHAPTER IV

Stochastic simulation model of Ankole pastoral production system: Model Development and Evaluation

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Abstract

In the Ankole pastoral production system animals are grazed on pasture all year round. The cattle are not supplemented with conserved pasture or commercial feed except minerals. The large number of factors that influence production makes it impractical and expensive to use field trials to explore all the farm system options. A model of a pastoral production system was developed to provide a tool for developing and testing the system; for example, drying off animals early and supplement them for quick return on heat, testing the economic and ecological viability of the different stocking rates. The model links climate information, on a monthly basis, with dynamic, stochastic component-models for pasture growth and animal production, as well as management policies. Some of the component models were developed and published by other authors but are modified to suit the Ankole pastoral conditions. The model outputs were compared with on-farm data collected over 3 years and data collected for other on-farm studies in the region. The relative prediction error (RPE) values for body weight after weaning across both breeds ranged from 3% to 12% which is below the acceptable 20% and means that the model predicts post weaning growth with an average error of 7.5%. The model predicted pasture production and milk yield across seasons with relative prediction errors of 17.6% and 3.33% respectively. The graph shapes of actual and predicted average daily milk yield as influenced by season (month of the year) were similar. Because pasture growth and milk production predictions were acceptable, economic predictions can be made using the model to test different management options such as seasonal breeding, alterations in lactation length and determination of appropriate off-takes and evaluation of economic viability of various stocking rates.

Key words: Ankole cattle, Pastoral system, simulation, STELLA software

4.1 Introduction

The production objective of Ankole pastoral system in south western Uganda is shifting from traditional subsistence to a commercial enterprise which is exhibited by the adoption of a new production system where farmers keep separate herds of

Ankole and Holstein Friesian x Ankole crosses on the same farm (Serunkuuma, 1998 and Wurzinger et al., 2008). Reasons as to why pastoralists keep two genotype herds on the same farm were discussed in details by Galukande et al. (2009). The production area is characterized by severe dry seasons and rains tend to be unreliable (Ocaido et al., 2009) and the effects are becoming more severe as human population increases, livestock and crop enterprises expand and restrictions that have been imposed on herd movements. The new system is bound to face a number of challenges and its success will depend on striking the right balance of all the variables involved which include; environmental conditions, health and productivity of animals of different genotype, management decisions and socio-economic issues. Many limiting factors decrease animal production: harsh environmental conditions like droughts; low nutritive value of tropical forage; high parasitic infection; and socioeconomic factors (e.g. land holdings changes from communal to individual ownership). It has been urged by Mohtar et al. (2000) that understanding the internal mechanisms by which major system components interact is essential for the development of good management practices that ensure maximum productivity and environmental sustainability. In order to support farmers' decision-making, modelling was identified as one useful technique that can be used to evaluate interactions among the major system components in the Ankole pastoral system. The current study aimed to assess the ecological and economic sustainability of the emerging Ankole production system through system analysis approach using a dynamic model to identify conditions under which either one or both genotypes can be kept on a sustainable basis by evaluating alternative production options. A stochastic pastoral farm model was developed based on components of existing simulation models (Blackburn and Kothmann, 1991; Diaz-Solis et al., 2003; Tess and Kolstad, 2000) which were modified based on local knowledge on environmental factors, animal genotypes and their nutrition and management practices. The dynamic herd based model simulated pasture growth, reproduction and production of the two cattle genotypes including management decisions made by the pastoralists. In this paper, we present the structure and evaluation of the model. The ability of the model to represent Ankole pastoral system under the range of conditions characteristic of

South Western Uganda is evaluated by comparing dynamically simulated and observed production parameters.

4.2 Materials and Methods

4.2.1 Study area and data collection

The study was carried out in Mbarara district of South Western Uganda. The topography consists of undulating hills and valleys. The hills rise about 100–200m above the flat valley bottoms. The area lies between 1250 and 1525m above sea level. Rainfall has in the past been reliable, but recent trends in rainfall patterns indicate more erratic behavior. The rainfall occurs in a bimodal pattern, peaking in the months of April to May and September to November. The current study used historical rainfall data for 46 years and obtained an annual rainfall mean of 939 mm. The months of June, July and August normally constitute a dry season with very little rainfall. Schwartz et al. (1996) have computed the mean annual rainfall for the Mbarara Meteorological site at Kakoba for the period 1980-1994 and obtained a figure of 882mm with a coefficient of variation of 20%. Mean maximum temperature is about 26°C and mean minimum around 14°C. *Themeda triandra*, *Cynodon dactylon*, *Panicum maximum*, *Brachiaria decumbens*, *B. platynota* and *Chloris gayana* are quantitatively the most valuable forage grasses for cattle. *Hyparrhenia filipendula*, *Loudentia kagerensis*, *Digitaria maitlandi* and *Sporobolus pyramidalis*, are less important due to their lower quality, but form a major component of the grass vegetation (Okello et al., 2005). Production and financial data from twenty farms were used as a basis for the modeling process to ensure that the modeled systems were based on real sets of resources that might be available to a farmer. The case study farms were selected to represent a range of farming systems in terms of farm size, grazing management and location.

4.2.2 Model overview

The model is represented as a stochastic compartment model based on difference equations with a time step of 1 month and is programmed in STELLA® (High Performance Systems, 2007). Developing sustainable management strategies in

pastoral systems requires a comprehensive understanding of the different aspects of the entire ecological-economic system. This concerns aspects such as the functioning of the ecosystem and the key factors of its productivity. World over, pastoral systems are found in arid and semi arid areas characterized by low amount and high variability in rainfall. This variability influences the dynamics of livestock feeding on vegetation. Therefore, the major elements in pastorals systems besides market availability are: precipitation, vegetation and livestock. The model is composed of four sub models namely the forage production, animal inventory and production, nutrient requirement and the economic sub-model. The model contains both deterministic and stochastic elements and the processes are simulated in separate sub-models, which are combined to make the overall model. Some of the model elements such as rainfall are subject to random variation and this is taken into account using relative cumulative frequency distribution constructed from historical rainfall data. The productivity of rangelands is influenced by many factors including rainfall and its variability between and within years and soil characteristics such as infiltration rates and water storage capacity. In addition, the transition in the status of each animal from one calendar month to the next during the simulated time period is determined by the set of biological processes and decision rules embedded in the model. At the beginning of each month of simulation, the model determines the forage quality and quantity on offer and the activity level of animals in the herd. Forage on offer is simulated independently, based on historical time-series data. The details of the forage component of the model are elaborated in the section below. Variation in rainfall both between and within years is stochastic hence model runs must be replicated before the probability of such changes may be predicted with confidence (Richardson et al. 2007). The results in this paper are means of 50 simulation runs. The simulation period was ten years. The detailed equations used in the model are presented in Appendix 4.

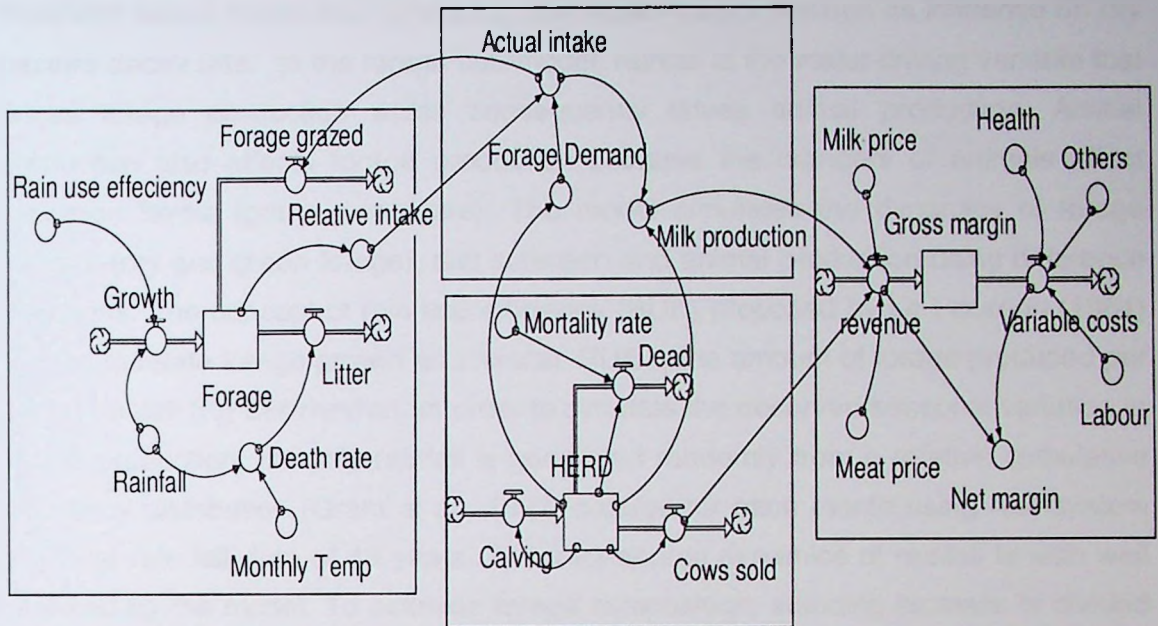


Figure 4.1: The conceptual model

4.2.3 Forage growth and dynamics

The pasture component is dynamic, and depends on the seasonal distribution of rainfall which affects forage availability and quality, as well as animal performance. Annual net primary production (ANPP) in grasslands (Lauenroth 1979), and particularly in semi-arid grasslands (Lauenroth and Sala 1992) is highly correlated with fluctuations in annual precipitation. The simplest approach to estimating potential pasture productivity for a particular soil type is to assume a linear relationship between potential production and rainfall (Scanlan et al., 1994). The pasture sub-model in this study is based on a model developed by Diaz-Solis et al. (2003) and later modified for north Texas by Sikhalazo (2005). However, the rangeland in South Western Uganda is tropical. In such areas radiation is not a limiting factor on plant growth (Pickup 1995) and it may be treated as constant or ignored. Also unlike in the temperate climate where temperature is the main controlling influence on growth, in the African savannahs and other dry lands, grass growth is controlled primarily by rainfall (Norman 2007). Temperature in Ankole region does not fall below the limiting

threshold hence it was also ignored in the model except through its influence on dry pasture decay rate. In the forage sub-model, rainfall is the major driving variable that drives forage production which consequently drives animal production. Animal production also affects forage production because the numbers of animals affect utilization levels (grazing pressure). The model simulates the dynamics of forage classes (dry and green forage), diet selection and animal production using difference equations. The concept of rain use efficiency (RUE) proposed by Le Houreou (1984) is used to relate forage growth and rainfall. RUE is the amount of forage produced per unit of rainfall (Kg DM/mm/ha). In order to simulate the observed seasonal variation in forage production, monthly rainfall is generated randomly from a relative cumulative frequency distribution (Grant et al., 1997) created for each month using real system historical rain fall data of 49 years. The inter-annual dynamics of rainfall is also well captured by the model. To estimate forage composition, standing biomass is divided into green pool (GP) and dry pool (DP). The green pool increases as a result of forage growth and reduces through senescence and being grazed by cattle. Forage growth is simulated on monthly basis using a multiplicative function of RUE and monthly rainfall (mm). When not consumed, the green pool undergoes senescence and flows into the dry pool. The daily senescence rate (0.0065) for vegetative sward used by McCall and Bishop (2003) was adopted, but modified to reflect a constant monthly senescence rate of 0.195. Some of the dry matter (25%) is lost from the system as a result of respiration while the rest turn into the dry pool (DP). The model is structured so that senescence occurs following grazing loss as suggested by Glasscock et al. (2005). The dynamics of DP is due to being grazed by cattle and decomposition. The rate at which the DP decomposes is determined according to the method developed by Diaz-Solis et al. (2003) and adopted by Sikkhalazo (2005) which was based on average monthly temperature and monthly rainfall, but all remaining dry herbage is decomposed in the months of May and September because during these months, a lot of rainfall is received hence only green forage is available in the range. The decomposition rate is given by the equation below.

Decomposition rate = $1 - \text{EXP} (-0.003077 * \text{MRF}) + 0.0005 * \text{AMT}$, where MRF is the monthly rainfall and AMT is the average monthly temperature.

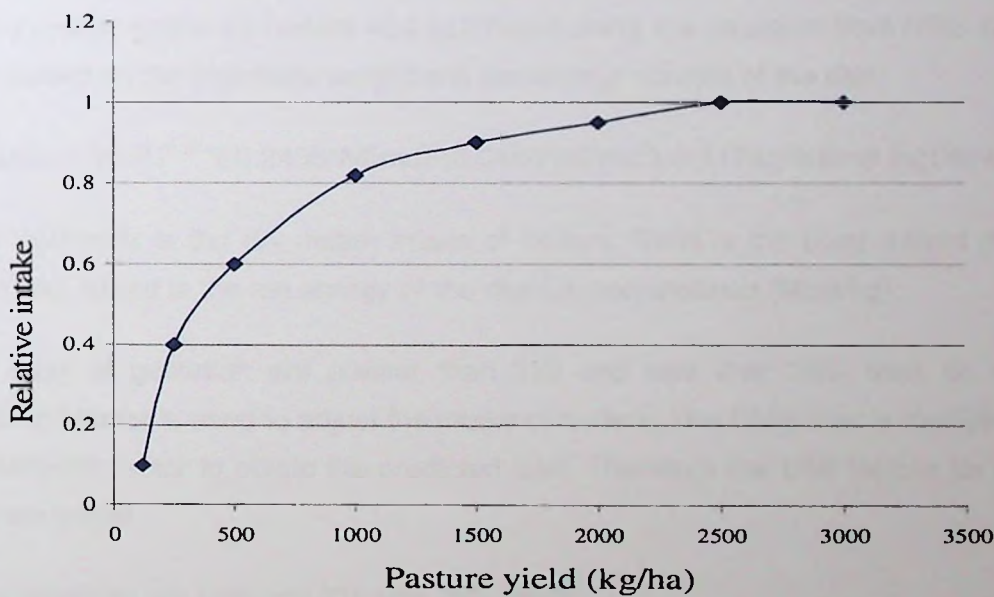
4.2.4 Grazing selection

The proportion of GP in the diet was obtained as the product of cattle preference for green pasture and its harvestability as explained by Blackburn and Kothmann (1991). Above some upper threshold, green pasture availability does not limit intake but as the availability of green pasture decreases below that threshold, its harvestability also decreases. The green pasture preference is calculated considering dry matter digestibility and crude protein contents of green and dry pool respectively. The crude protein and digestibility data reported by Okello et al. (2005) and Byenkya (2004) were used. Individual monthly crude protein and digestibility were used in the model so as to determine the proportion of the dry and green pasture in the diet. Digestible organic matter (DOM) values reported by Byenkya (2004) were converted to digestibility as $(DOM + 2)/0.95$ according to AAC (1990) to estimate the corresponding monthly digestibility of the pasture. Data on the monthly crude protein and digestibility of dry pool was not available. However, discussions with experts on forage studies in the study area and also basing on personal observations in the field, it was agreed that during the month of July, pastures in the range are in the form of dry pasture with very minimal green pasture. Therefore, an assumption was made that the value for digestibility and crude protein of pasture reported for July represent the digestibility and crude protein for the dry pasture pool for all the months of the year. Hence constant single values for either digestibility (64.28%) or crude protein (6.42) of dry pasture were used in the model. The model also considers the argument by Grant et al. (1999) that cows consume all available green vegetation before dry vegetation to meet their forage requirements. As in the study by Freer et al. (1997) the cattle consumed the available green and dead dry matter from the most digestible pools until potential dry matter intake was satisfied or all the available pasture was eaten.

4.2.5 Dry Matter Intake

In their study of comparative mathematical and conceptual analysis of quantitative feed intake prediction models for cattle, Pittroff and Kothmann (2001) concluded that there are few models available for estimating forage intake of grazing animals and that two widely used standard systems for calculating nutrient requirements for cattle,

NRC and ARC, seem to be not adequate for application in grazing situations. To partly address the above concerns, in this study, potential voluntary intake (PVI) is calculated according to NRC (2001) as well as MAFF (1975) and actual dry matter intake (DMI) is calculated as a proportion of potential DMI depending on the pasture dry matter yield. As yield declines, so too does the ability of the animal to reach its potential DMI based solely on forage quality (Charmley et al., 2008). Therefore, to adjust the intake values provided by the NRC (2001) intake equation, a relationship developed by Coleman (2005) was adopted for this study (Figure 2). A similar approach was used elsewhere in Jouven et al. (2008). The intake subcomponent of the model calculates the voluntary intake of forage by grazing animals.



Source: Coleman (2005)

Figure 4.2: Relationship between DM yield and potential intake for low relative pasture availability

The following equation was used to calculate the intake of lactating cows.

$DMI_{lact} = (0.1 \cdot FCM + 0.025 \cdot BW_{Lact})$ {kg DM/day}, where DMI_{lact} is the dry matter intake for lactating cows, FCM is the fat corrected milk (Kg/day), BW_{Lact} is the body weight of lactating cows. The equation to calculate the FCM is given below:

$FCM \text{ (kg/day)} = (0.4 \cdot \text{Milk production}) + (15 \cdot (MILK_{Fat}/100) \cdot \text{Milk production})$, where $MILK_{Fat}$ is fat content of milk in percent. If the days of gestation are greater than 259, the equation for dry matter intake of dry cows is given by NRC (2001):

$DMI_{dry} = (((1.97 - (0.75 \cdot e^{(0.16 \cdot (Days_{Preg} - 280))})) / 100) \cdot BW_{Dry})$, where DMI_{dry} is the dry matter intake in the last 21 days of pregnancy, $Days_{preg}$ is the day of gestation and BW_{Dry} is the body weight of dry cows.

The dry matter intake for heifers was estimated using the equation from NRC (2001) that is based on the metabolic weight and the energy content of the diet.

$DMI_{heifer} = (BWH^{0.75} \cdot ((0.2435 \cdot NEmd) - (0.0466 \cdot NEmd^2) - 0.1128)) / NEmd$ {kgDM /day},

where DMI_{heifer} is the dry matter intake of heifers, BWH is the body weight (kg) of heifers and $NEmd$ is the net energy of the diet for maintenance (Mcal/kg).

If the days of gestation are greater than 210 and less than 259, then an intake adjustment factor is used to adjust the intake of heifers. The DMI_{heifer} is multiplied by the DMI_{heifer} factor to obtain the predicted DMI. Therefore the DMI factors for heifer are given below.

If days pregnant are between 210 and 259, then:

$DMI_{heifer} \text{ factor} = 1 + (210 - \text{days preg}) \cdot 0.0025$ or if days pregnant are greater than 259, then:

$DMI_{heifer} \text{ factor} = (1.71 - (0.69 \cdot e^{((0.35 \cdot (Days_{Preg} - 280))))) / (100 \cdot BW_{HP})$

The pre-weaning pasture intake by calves is assumed to begin actively at 61 days after calving, because very young calves consume insignificant amount of forage as they can not digest a greater intake.

Dry matter intake by male weaners was estimated using the equation from NRC (1984) that is based on metabolic weight and the energy content of the diet:

$$\text{DMI weaned male} = \text{BWm}^{0.75} \times (0.1493 \times \text{NEmd} - 0.046 \times \text{NEmd}^2 - 0.0196) \text{ \{kgDM /day\}},$$
where BWm is the body weight of the steer and NEmd is the net energy in the diet (Mcal/kg DM).

The voluntary dry matter intake is then corrected for availability of forage. The outputs generated from the intake subcomponent (dry matter intake for each animal category) are used as input in the energy requirement sub-component of the model.

4.2.6 Nutrient requirement

The requirements for the net energy were based on the factorial method in which the NE consumed is portioned into the amount of energy required for the maintenance, gestation, lactation, weight change and grazing activity. All these requirements were determined according to NRC (2001) and CSIRO (1990). Days in milk, milk fat, milk production, body weight, mature weight and day of gestation are inputs from the herd component.

Maintenance requirements: The maintenance requirement is determined as a function of body weight (BW). Using the equations of NRC (2001) and CSIRO (1990), total maintenance requirement for lactating cows was obtained as follows:

$$\text{NE}_{\text{maint}} (\text{Mcal/day}) = 0.080 \times \text{BW}^{0.75} + \text{NE}_{\text{act}},$$
Where NE_{maint} (Mcal/day) is the net energy for maintenance, BW is the body weight (kg) and NE_{act} is the net energy requirement for activity and grazing. The grazing and walking requirements estimate the amount of energy used by the grazing animal. It includes the energy expenditure per kg body weight and affects forage energy availability. Using CSIRO (1990), the

activity requirements (NE_{act}) for all cow cohorts were calculated in the model as follows:

$$NE_{act} = ((0.006 \cdot DMI \cdot (0.9 \cdot FDMD)) + (0.05 \cdot 1.5 / ((0.002471 \cdot \text{Green_forage} + 3))) \cdot BW) / 4.186 \text{ [Mcal/d]}$$
where DMI (kg/day) is the dry matter in take, FDMD is the green forage dry matter digestibility, BW is the body weight of the animal.

Since the Ankole cattle belong to the Sanga group of cattle with a considerable proportion of *bos indicus* genes, the maintenance energy was decreased by 10%, a recommendation adopted from the (NRC 2001).

Pregnancy requirement: The energy required for pregnancy is assumed to be zero when days of gestation (DOG) is less than 190 days and the maximum gestation length was set to 279 days. The pregnancy requirement was estimated by NRC (2001) equations.

$$NE_{preg} \text{ (Mcal/day)} = (((0.00318 \cdot DOG - 0.0352) \cdot (CBW/45)) / 0.14) \cdot 0.64$$
where CBW is the expected calf birth weight calculated as $CBW = MW \cdot 0.06275$, where MW is the mature weight and DOG is the day of gestation. The constants used in the equation are: 0.64 = conversion of the Metabolisable energy (ME) to Net energy, 0.14 = the efficiency with which metabolizable energy is used for pregnancy.

The Net energy NE_c content in the forage was obtained using the equations from MAFF (1984).

$$ME \text{ (MJ/kgDM)} = (((DMD - 61) \cdot 0.011) + 3.2) / 4.186 \text{ (Mcal/kg)},$$

$$NE_c = (ME + 0.2473) / 1.8315 \text{ (Mcal /kg)}$$
Where, DMD is the digestible organic matter in the feed dry matter and constant 4.186 converts Mega joules to Mega calories, DMD is the monthly in vitro dry matter digestibility of the forage.

Consumption of metabolizable energy was determined by fodder consumption and the metabolizable energy contributed by it. Hence the monthly net energy intake (NEI)

for the respective cow cohorts was then obtained by the product of net energy content (NE_C) in the feed and the dry matter intake (DMI).

$$NEI = DMI * NE_C * 30.4 \text{ (Mcal /month)}.$$

4.2.7 Herd structure

The herd inventory sub-model is used to: Simulate dynamics of age groups in a cow herd (from birth to 9 years old); predict the number of replacements heifers, cows and culled cows and also mortality rate for the various cohorts; Predict energy and dry matter intake for each cow cohort and for the herd based on the outputs of the nutrient requirements sub-model, which estimates the nutrient requirements for average animal in a cohort. The model determines the changes taking place in each animal's status during the month of simulation, using endogenous biological processes regulated by exogenous management policies. Animals are considered as juveniles from birth to 27 and 24 months of age for Ankole and Ankole-Friesian crossbred herds respectively. After the above ages, juveniles join the reproductive herd. The cows are grouped into cohorts depending on their age and physiological status hence the herd is divided into the following groups: calves, yearling, replacement heifers, pregnant heifer, and cows. Cows are further grouped according to parity number into lactating, pregnant and dry cows. The herd structure is established according to pregnancy, calving and mortality rates of each of the cohorts. The input variables include the number of animals and weight of each category. Upon calving, heifers automatically join the first parity lactating cows. After calving, cows attain postpartum estrous two months after calving. The number of females in the herd is input at the start of the model run. Farmers do not keep male calves on their farms beyond one year of age, hence male animals are included in the model but they were all culled at the age of one year. Heifers reach puberty at 24 months of age (for crosses) and 27 months (pure Ankole cattle) and calvings occur in any of the twelve months of the year. The maximum lactation number of lactation allowed is 6 (crosses) and 8 (pure Ankole) after which the cow is culled. For each parity status (nulliparous, primiparous and multiparous cows), the reproductive cows

are grouped by their physiological status (9 months of gestation and postpartum anoestrus; one status for non pregnant cows and heifers). The herd structure sub model generates numbers of animals of different classes to be used in the nutrient requirement and forage sub-model to determine the herd forage DMI. It traces the numbers of offspring of different classes (sex and breed) produced by the cow throughout her life in the herd. The number of births at a given time is equal to the number of cows calving i.e. cows that have calved and survived. Calves are assumed to be born alive. The model assumes that the calves are born in the ratio of 1:1 males to females. Conception did not depend on the nutrient status of the cows and this could be one of the weaknesses of the model, but it was catered for by simulating conception stochastically (using the inbuilt function of STELLA called RANDOM (2, 5) where cows conceived between two to five months after calving. Natural mating is used in this production system where each herd has at least one mature bull which grazes with the females all the time.

The module calculates the number of males and females of each stage (infants, juveniles, and adults), the number of deaths for each stage, and the number of individuals transitioning between stages. In order to capture the age specificity and physiological status of the different animal cohorts, conveyers were used to represent them. A conveyor is a specialized stock variable in STELLA. Stock variables accumulate the individuals that flow into them; a conveyor accumulates individuals in a similar way, but can retain its individuals for a specified amount of time. By treating some stages as conveyers, some of the realities of age-specific models are retained while still working within a stage approach. The stages are initialized with starting densities for males and females; the stage retains these initial individuals for specific stage duration and simultaneously accumulates individuals transitioning in from the previous stage. The stage tracks how long individuals have been in the stage and transitions them to the next stage after the stage duration has passed. While in a stage, individuals are susceptible to death via a stage-specific mortality rate. Unlike in previous studies like Kothmann and Smith (1983); Diaz-Solis et al. (2003) and Sikhalazo (2005) where stocking rate was held constant, in this study stocking rate is dynamic and changes over the course of the simulation time.

4.2.8 Milk production and animal growth

This model computes the lactation curves of group of animals calving in a particular month according to its breed, stage of lactation (month) and yield potential, taking into account an effect of energy intake. A study by Jenet et al. (2004) on the lactation curves of *taurus-indicus* crossbreeds showed that they do not follow a typical Wood (1967) curve. To simulate the potential milk yield, the study adopted Fox et al. (2004) equation in which milk production for primiparous and multiparous cows was determined as a function of time in lactation and the potential peak milk yield which is given by: $(PMY = n/(a \times e^{kn})$ where PMY = milk yield during month n of the lactation cycle, kg/d; $a = 1/(PKYD \times (1/T) \times \exp(1))$; PKYD = peak milk yield during the lactation, kg/d; k = shape parameter, $1/T$; and n = time since calving, months, and T = month of peak lactation. The actual milk production was then determined by adjusting potential milk yield according to Tess and Kolstad (2000) which is based on the amount of energy available for lactation. The energy content in milk (NE_{milk}, Mcal/kg) was computed using multiple regression equation (MAFF 1975): Milk energy content = $(0.386 F + 0.205 SNF + 0.236)/4.186$, Where, F and SNF represent percentages of fat and solids-not-fat, respectively and 4.186 constant converts MJ to Mega calories. The fat content of the crossbred was taken to be 3.5% while the pure Ankole have a fat content of 5.25% (Petersen et al., 2003). The study adopted Ankole cattle lactation and milk characteristics reported by Ndumu (2000) namely peak milk day (45), peak milk yield (3 kg), mature weight (317 kg), milk solids (8.3%), milk fat (5.45%), milk protein (3.4%), lactation duration (212 days). In the event that milk production is greater than the corresponding potential on a given day, the milk production was equated to the potential and with the result that the surplus energy will be destined to weight gain. Milk yield was modeled for an average group for each month of calving rather than for individual cows. In otherwords, each calving group maintains it own days in milk to correctly manage the events of the calving cycle. Genetic potentials are regarded as maximum levels of performance obtainable only when sufficient nutrients are consumed.

Growth of steers is determined based on the energy available for growth and an equation developed by Smallegange and Brunsting, (2002) was adopted.

Growth rate = $E_bal / (20.06 \times 0.2788 / \text{Weight_ebw}^{0.1107} + 33.41 \times 0.0039388 \times \text{Weight_ebw}^{0.788})$, where Weight_ebw is the empty body weight, and E_bal is the energy balance.

$\text{Weight_ebw} = 0.91 \times \text{Weight} \times 550 / \text{Weight_ad}$, where Weight is the current body weight and Weight_ad is the adult body weight

The weight of the animal is calculated each month by:

$\text{Weight}_{(t+1)} = \text{Weight}_{(t)} + \text{Growth rate}$

4.2.9 Economic sub-model

The economic sub-model measures bio-economic efficiency by subtracting total cost from total return. Total return is estimated from the sale of weaned calves, heifers and culled cows as well as milk sales. Total cost is the sum of variable costs. Variable costs included expenses such as labour, pasture improvements costs and veterinary service.

4.2.10 Statistical criteria for model evaluation

Model validation is a test of the ability of the model to accurately assess the intended application (Sørensen, 1990). The actual data was obtained from a 3-year longitudinal study carried out in the same study area (Galukande 2010). In this study the model results were compared with the observed values of animal body weight from weaning to 18 months of age, average daily milk production and monthly forage yield. The model testing was done using statistical approaches as summarized by Schaeffer (1980) and recently adopted by several authors (Shah and Murphy 2006; Beukes et al., 2008; Dijkstra et al., 2008 and McEvoy et al., 2009). Mean absolute error (MAE) was defined as $(\sum |O_i - P_i|) / n$. Relative prediction error (RPE), which is MAE as a proportion of observed mean values, $RPE = MAE / [\sum (O) / n]$, was used to determine precision and reproducibility of prediction. Values for RPE less than 0.10, 0.10–0.20 and >0.20 indicate good, moderate and poor simulation adequacy, respectively (Beukes et al., 2008; Bryant et al., 2008; Fuentes-Pila et al., 1996). The

same criterion was applied to measure general model efficiency where predictions were compared with observed data. Further evaluation was done using graphs that presented both observed and simulated data. Technical evaluation was also made to find out whether the model components were behaving in a manner that is expected in real system based on published information rather than simply the extent to which they track the data accurately.

Table 4.2: Some of the model input parameters

Parameter	Parameter value	
	Ankole cattle	Ankole-Friesian
Potential milk yield (kg)	6	18
Weaning age (months)	7	7
Milk fact content (%)	5.25	3.5
Milk solids (%)	8.3	8.3
Lactation length (months)	211	270
Mature weight (kg)	360	460
Open period (months) (stochastic)	2-5	2-4
Gestation length (days)	280	280
Dry period (months)	2	2
Mortality rate pre-weaning (%)	5	7.1
Mortality rate for heifers (%)	5.3	7.3
Mortality rate (2- 9 years) (%)	4.2	6.5
Grazing area (ha)	200	200
Serving bulls	2	2
Cows	61	76
Heifers	35	36
Steers	12	10
Weaner bulls	14	10

4.3. Results and Discussion

4.3.1 Model evaluation against field data and model behaviour

Model validation is dependent upon quantitative and qualitative analyses of differences between simulated and actual data (Shalloo et al. 2003) and the essential requirement when building a model is that it should adequately represent the system (Damborg, 1985) under study. The evaluation determines the extent to which simulated results match actual data and, therefore, test the assumptions inherent in the model structure and function. In the present study, there was good agreement between the actual farm data and the simulated results. The calculated MAE and RPE for dry matter yield, average daily milk production and body weights are presented in Table 2. The RPE value of 0.075 for growth (body weight) after weaning across both breeds is below the acceptable 20% (Schaeffer 1980; Shah and Murphy 2006; Beukes et al., 2008; McEvoy et al. 2009) and means that the model predicts post weaning growth with an error of 7.5%. This exercise showed that the model has the potential to give acceptable predictions of animal growth. The data used for evaluation of the model with regard to monthly dry matter yield (DMY) was done using data collected from the study area in a period of three years (2005 to 2008). The RPE value of 17.6% for monthly dry matter indicates relatively higher error of prediction. Predictions for DMY were also presented in Figure 3. The months of April and December are greatly under predicted but this could be due to the quality of data used for evaluation. These months had data obtained from a single year of production rather than across all the three years and yet it was reported by Mulindwa et al. (2009) that there is substantial within year variation in pasture production in the study area. Evaluation of variation in the biomass yield is further illustrated using the example of milk production. Milk production cannot be ignored from the economic viewpoint as it is the major source of daily income for the pastoralists in South Western Uganda. Observed data are average daily milk production on the farm. The results show that the model satisfactorily simulated the daily milk production with prediction error of 3.3%. The graph shapes (Figure 4) of actual and predicted average daily milk yield as affected by month of the year were similar which indicates that the model has the capacity to capture the season influence on milk production due to

changes in the forage quality and quantity. Another indicator for evaluation of the model was simulated growth rates (Figures 5 and 6) for steers and heifers (from weaning 7 to 18 months) evaluated against research results (Galukande 2010) for the same production environment in Uganda.

Table 4.3: Statistical parameters, observed and simulated dry matter yield, post weaning body weight (7 to 18 months) and milk production

Parameters	Mean values and statistical parameters					
	Observed	SDo	Simulated	SDs	MAE	RPE
DMY (kg/ha)	2079	536	1943	203	367	0.176
Pure Ankole						
Female BW (kg)	129.50	12.05	139.77	18.89	11.17	0.08
Male BW (kg)	113.36	12.42	115.40	17.58	8.39	0.07
Ankole-Friesian crosses						
Female BW(kg)	163.69	20.18	142.01	21.74	21.00	0.12
Male BW (kg)	161.06	27.06	158.57	24.55	4.57	0.03
Milk (kg/day)	7.02	0.40	7.14	0.88	0.63	0.033

MAE = mean absolute error, RPE = relative prediction error, and SDo = standard deviation for observed values, SDs = standard deviation for simulated values, BW= body weight, DMY= dry matter yield

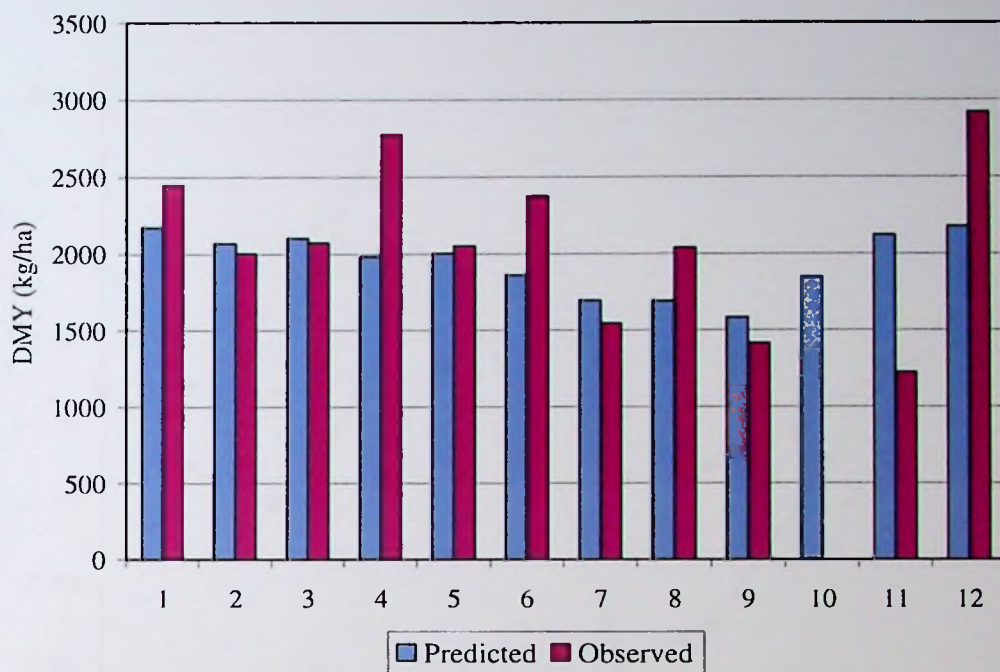


Figure 4.3 Observed and simulated dry matter yield (DMY) in south western Uganda

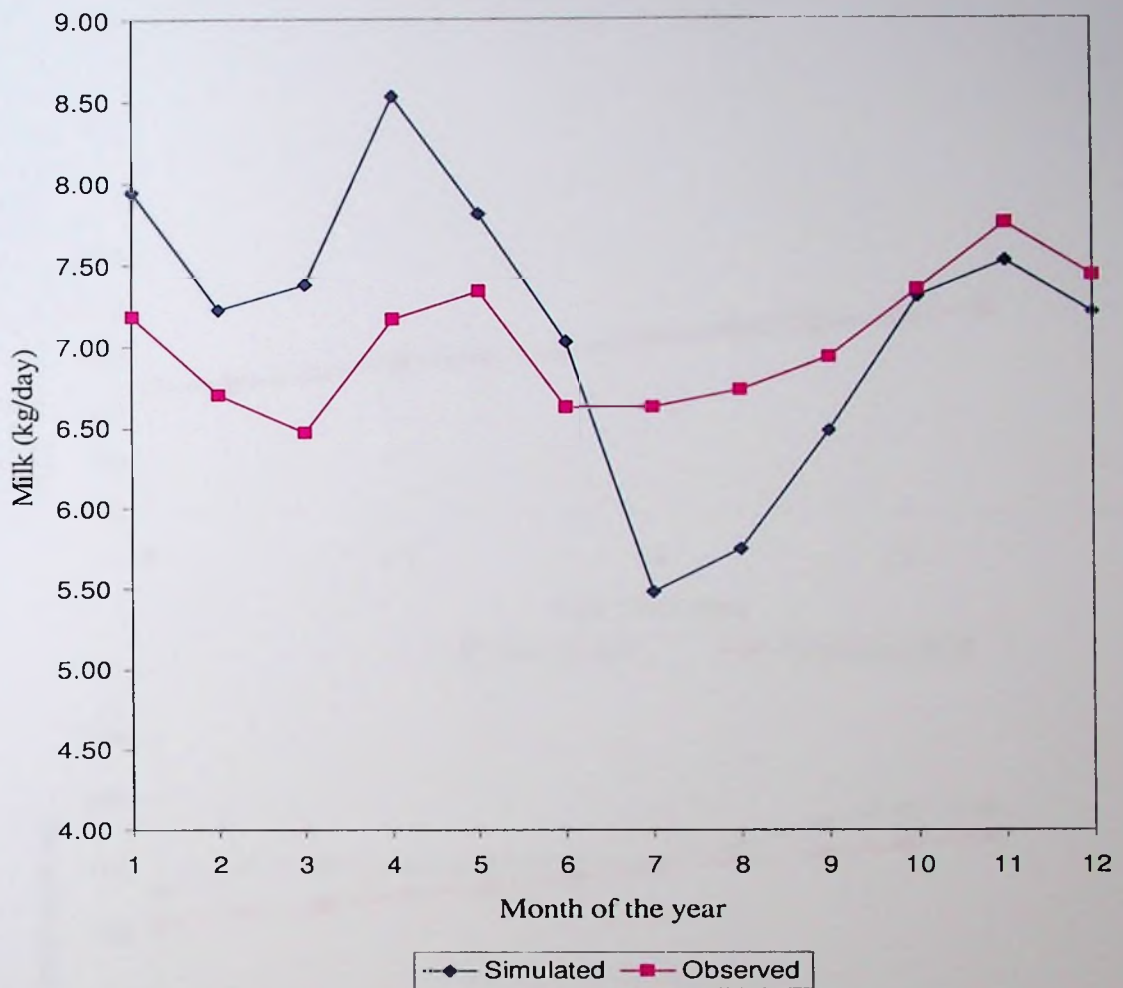
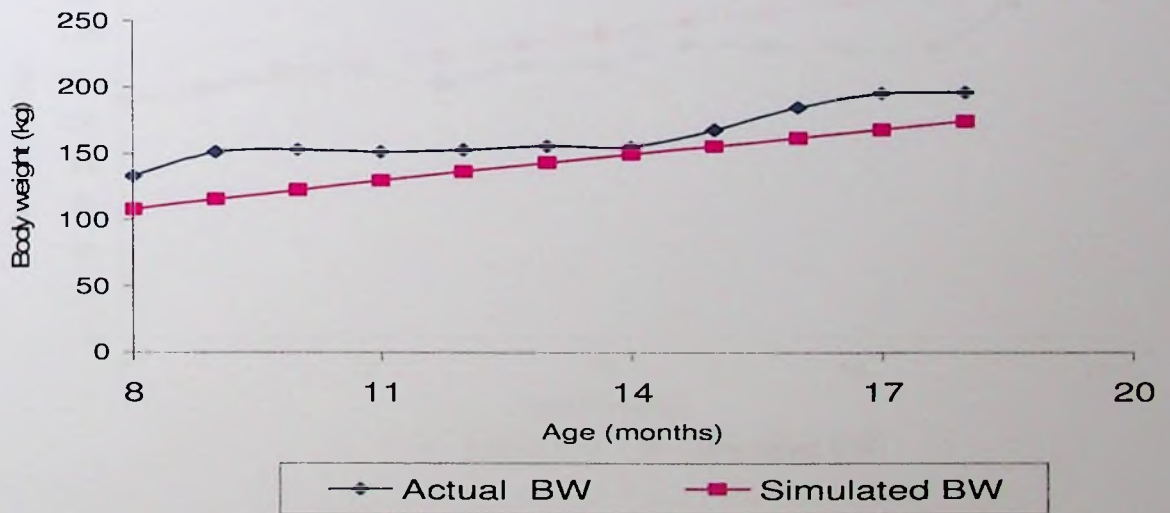
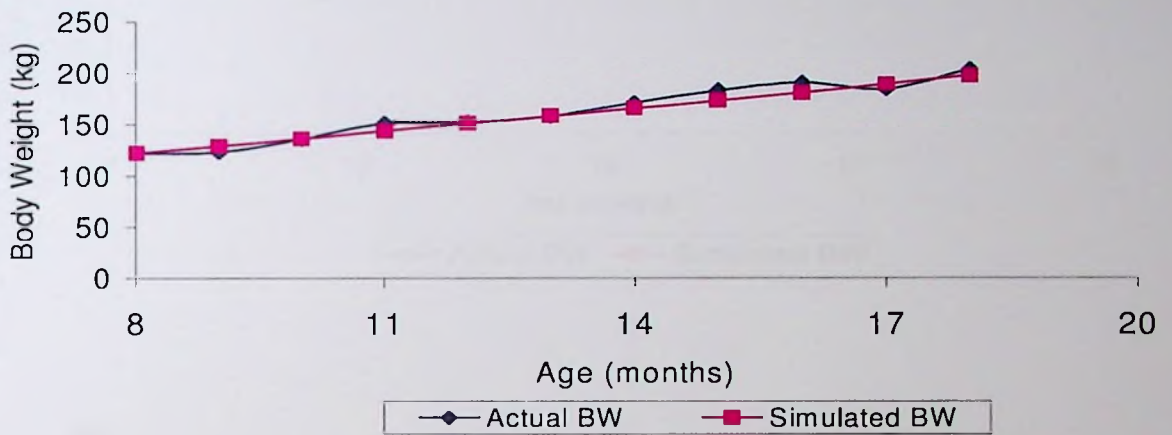


Figure 4.4: Comparison of simulated and observed mean monthly milk yield for Ankole-Friesian crosses

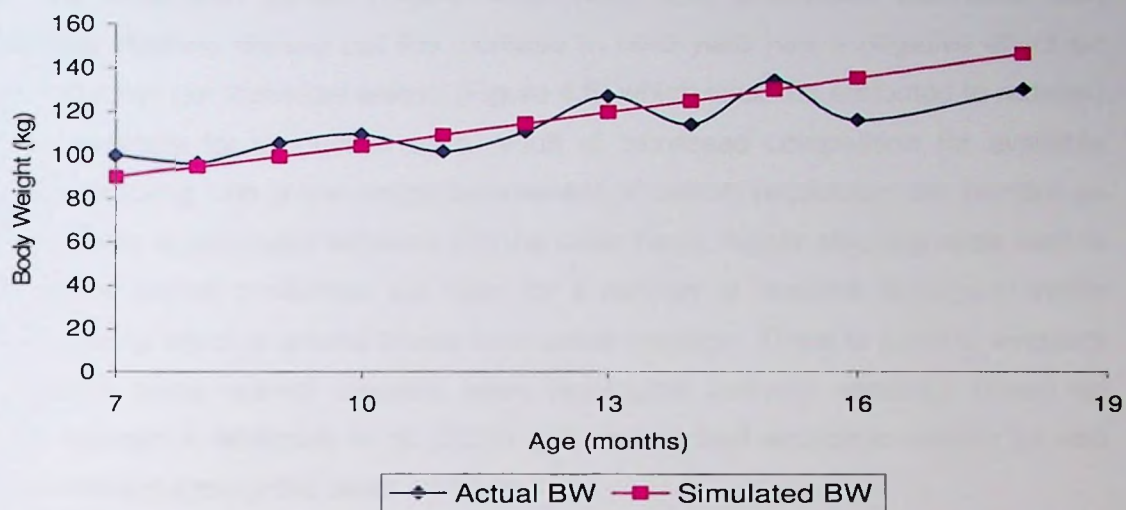
a)



b)

Figure 4.5: Observed and simulated post weaning body weight Male (a) and female (b) Ankole- Friesian crossbreds

c)



d)

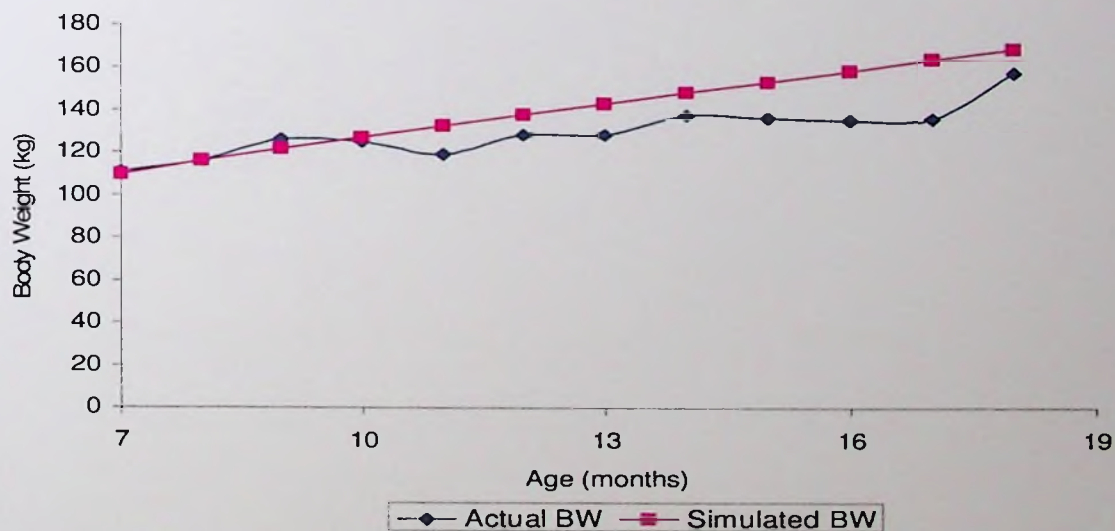


Figure 4.6: Observed and simulated post weaning body weight of male (c) and female (d) pure Ankole

The model also predicted changes in herd milk production throughout the simulation for a herd that was managed by the same rules but grazed at dynamic stocking rates over the simulation period (Figure 4.7). Herd milk production increased with increasing stocking density but the increase in herd yield had a negative effect on milk production per individual animal (Figure 4.8) which could be attributed to reduced energy available for production as a result of increased competition for available pasture. Stocking rate is the major determinant of animal production per hectare as more animals supply more produce. On the other hand, higher stocking rates lead to reduction in animal production per head for a number of reasons detailed in White (1987) among which is animal stress from under nutrition. There is need to evaluate the system using optimal stocking rates (ecological carrying capacity) based on values reported in Mulindwa et al. (2009) and assess their economic viability as well as determining appropriate cattle off-takes.

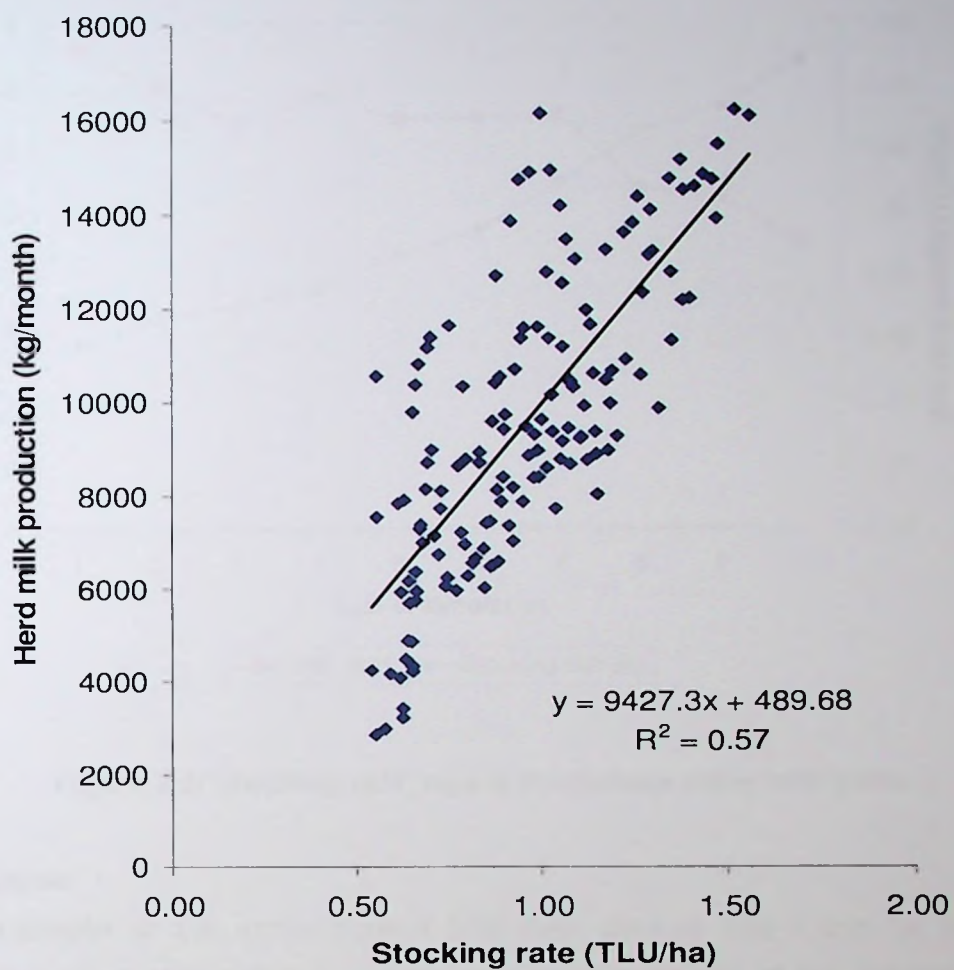


Figure 4.7: Stocking density effect on herd milk production

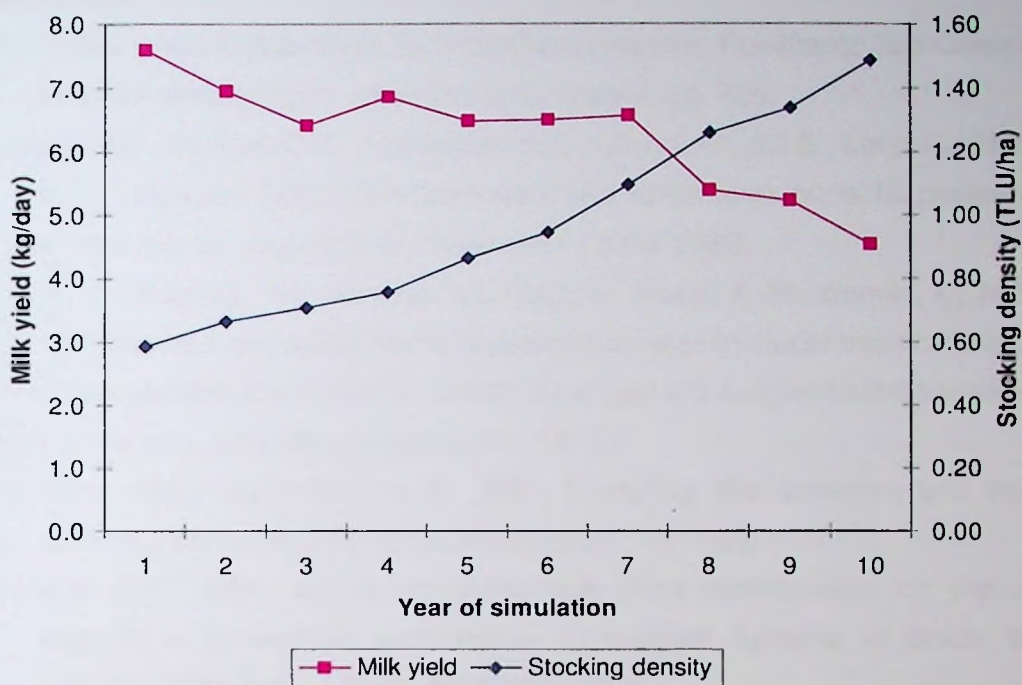


Figure 4.8: Stocking rate impact on average daily milk yield

Conclusion

The evaluation of the model against field data showed that it can be used in evaluating some strategic and tactical management options of the grazing based dairy/beef system in South Western Uganda. However, there is need to validate the model using other model parameters and field data from other areas with similar climatic conditions and farming systems before it can be applied on a wider scale.

Acknowledgment

The authors acknowledge the Government of Austria for financial support through Austrian Development Agency.

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CHAPTER V

Economic and ecological evaluation of alternative management options in Ankole pastoral system

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Abstract

A study was carried out to evaluate alternative management strategies for components of beef and dairy production pastoral systems and interactions among those components. A stochastic simulation was developed in STELLA software was used to evaluate three management strategies that included reduction on open period and shorter lactation length (1), optimum stocking rates (2) and restricted breeding season (3). Economic analyses were conducted for each of the options and some of their combinations. In scenario 1, the average monthly and annual incomes were higher by 17.3% in the control scenario than in the scenario 1. Though both scenario 1 and control group had relatively similar average TLU, the herd value of scenario 1 was 23% higher than the control group. In scenario 2, the optimal stocking rate set at 1.5ha/TLU had a higher (by 2%) income compared to the control group even though its overall average TLU was smaller by 28.28 TLU. Daily milk yield in the Ankole-Friesian crossbred herd was generally higher (0.25kg) in the restricted breeding season than the year round breeding. The reduction in the open period length for the Ankole herd marginally improved the monthly gross income compared to the control group but both scenarios resulted in monthly net losses with exception of a few months when more animals were sold. Adoption of restricted breeding season would substantially improve the efficiency of the production system due to more milk harvest as well as improved quality of the herd. The stocking rate that is ecologically sustainable and economically viable for Ankole pastoral production system has been found to be around 1.5ha/TLU. A stocking rate below 1ha/TLU is economically viable but ecologically unsustainable whereas a stocking rate above 2ha/TLU is ecologically sustainable but leads to under utilization of the rangeland. If pastoralists are to adopt management methods (supplementary feeding of lactating animals) aimed at reducing the open period among the pure Ankole cattle, the benefits would be realized after a period of three years.

Keywords: Simulation, restricted breeding, Ankole-Holstein Friesian crossbreds

5.1 Introduction

Cattle breeding strategies in Ankole pastoral production system in the south western Uganda are characterized by high potential, but also by many difficulties. The traditional cattle production based on pastoral grazing has been influenced by a recent improvement in infrastructure as well as the organization of milk collection and processing which has led to new market outlets (Petersen et al., 2003). These new opportunities for commercial milk production have encouraged cattle keepers to gradually improve their management practices, including bush clearance for improvement of the pastures as well as upgrading their cattle by crossbreeding Ankole cows with Holstein Friesian bulls. The relatively high annual rainfall offers two growing seasons that result in high potential forage production, but environmental and nutritional stresses on livestock are great during dry months as well as high disease burden in the rain seasons. Pastoralists must therefore cope with the effects of low levels of digestible energy and protein in the forage during the dry seasons. Surprisingly a study (Smith et al., 2008) on the milk progesterone profiles of pure Ankole and Ankole-Friesian crossbreds reported that crossbreds had a high ovarian activity even in the dry season. Although early ovarian activity may not always translate into estrus signs, those findings indicate that provided these animals are given some supplements especially in the early lactation, chances of early conception are high. If the production efficiency and sustainability of the current system is to be enhanced, appropriate innovations and management practices must be introduced into the present traditional grazing system. Sunderlin (1995) noted that the meaning of the concept of sustainable development lends itself to widely varying interpretations whereby it needs to be both spatially and temporally defined in the sense that what is sustainable at one scale may not be at another, what is sustainable in the short-term may not be in the long-term. In the context of extensive pastoral enterprises, a common element of most definitions is the dual recognition that pastoral production enterprises need to be economically viable and the underlying processes ecologically viable (Bellamy and Lowes 1999).

Management alternatives such as season of calving; early drying of cows accompanied by supplementary feeding of lactating cows; use of optimum stocking

rates to determine off-takes all could have significant impact on the productivity of a pastoral farm. Their cost effectiveness and economic viability need to be evaluated and yet not all possible management combinations in a field research program are practically possible.

There has been an attempt in the past (Sullivan et al., 1981) to include stochastic weather variables into an interactive forage model to simulate the effects of unpredictable weather on production patterns found in East Africa. In the current study a dynamic simulation model was built based on the management policies used in Ankole pastoral production system where farmers keep two separate herds of cattle (pure Ankole and Ankole-Friesian crossbreds) on the same farm. The aim was to determine conditions under which either one or both types of herds can be raised on sustainable basis. The main goal of building most models is to test model behavior in the future while varying parameters of interest. There is a clear difference between assuming that a model will accurately forecast the future and using the model as a tool: "A forecast is an attempt to predict what will happen. A projection is an attempt to describe what would happen, given certain hypotheses" (Caswell, 2001). We used a dynamic model to ask what would happen to the performance of the Ankole pastoral production system if the current management practices are maintained or altered in specific ways. In this paper results from a simulation experiment comparing traditional grazing practice and cattle management with a range of alternative management options for Ankole rangelands in South Western Uganda are presented.

5.2 Materials and Methods

The model used to evaluate alternative management options is explained in detail in chapter IV. The model was parameterized to represent the characteristics of the respective cattle genotypes (Ankole and Ankole-Friesian crossbreds). The model consists of four sub-models (herd, pasture production, nutrient intake and requirement as well as the economic sub-model) details of which are explained in chapter IV. The simulations were carried out using the graphical simulation environment of STELLA version 9.0.2 (High Performance System Inc., Hanover, New Hampshire). The simulation time unit was "month" and a long-term time horizon of

120 months (10 years) was considered. The stochastic element of the model relates to the use of random drawings from relevant distributions for simulating monthly rainfall and events for (open period) group animals. The mechanistic part relates to the fact that the model simulates two organizational levels: the animal level and the herd level. Prices were assumed fixed throughout the 10 year simulation period. Since the model included some stochastic variable, the results presented are means of 50 simulation runs. The model predicts growth rates, fertility (open period length), deaths and milk production from the genetic potential of the cattle interacting with the quality and availability of feed resources. Breed type for size, maturing pattern, and milk production potential, culling and selling policies, and forage quality and availability were set in the model. An animal's nutrient intake relative to its requirements could cause its milk yield to deviate from its potential yield and periods of severe nutritional stress could cause reduction in production. Genetic potential for milk production was specified for a mature cow (within a breed) in good condition at peak lactation receiving abundant feed. In the model, the effects of stage of lactation and nutrition determined actual production. In the model the costs of production (labour, feeds, mineral salts, drench and drugs) vary according to the herd size and were set up to be fixed on per TLU per month basis. As the herd increased, the proportion of a particular cost item (labour cost) per number of animals was decreased to optimize costs. The prices of concentrate, milk, heifer, steers, cows, labour, drugs and mineral supplementation were based on averages found in the region (South Western Uganda) as well as from farmers' interviews. To create the base data set (control), the model was run without making any major alterations. The model was later used to simulate and evaluate a number of scenarios described below. Each of these management practices (scenario) was examined individually and in combination to determine their net benefit to the livestock keeper in terms of revenue and quality of the herd.

5.2.1 Scenario 1: Altered open period and lactation length

A study by Galukande (2010) reported an average open period of 6.3 months for the Ankole-Friesian cattle under natural grazing and natural mating which indicates long

calving intervals within the system under study. A study undertaken at Namulonge (NARO/NAARI 1996/97) to determine the optimum levels of lablab hay and concentrate supplementation to lactating crossbred cows revealed that additional feeding levels of dairy meal above 2 kg did not cause significant increase in milk yield and concluded that lactating cows producing less than 10 kg of milk required amount of dairy meal not exceeding 2 kg/day for optimal production. In another study, Kabirizi et al. (2006) reported that the interval between calving to conception was shorter (73-78 days) in supplemented cows compared to unsupplemented cows (101 days). A study done by Msangi et al. (2004) showed that short-term supplementation to crossbred dairy cows promoted post partum early ovulation and significant improvement in the number of cows showing estrous suggesting that energy balance is implicated in moderating the occurrence of oestrous behaviour. In addition, *Bos indicus* crossbred cattle tend to have high milk production in the early stage of lactation which drastically drops in the late stage of lactation (Herrero, 2009, personal communication) an indication of their high efficiency in the early stages of lactation. The above phenomenon is clearly shown by Nouala et al. (2003), studying on the Ndama cattle crosses with Holstein Friesian and Jersey. In line with the above findings and observation, the current study evaluated the lifetime economic performance of the herd by reducing the interval (open period) between calving and conception through supplementation feeding as well as shortening the lactation length in crossbred cattle.

In creating the base data, the cows' conception was set by considering a randomly initiated open period using an inbuilt function RANDOM (2, 6), within STELLA where 2 and 6 is the minimum and maximum time (months) that elapses after calving before an animal conceives. In Scenario 1, the open period was set to two months and the lactation length reduced to six months, and tested to evaluate its overall impact on the performance of the system. Basing on the findings in earlier studies (Kabirizi et al., 2006, Msangi et al., 2004), an assumption was made that supplementing lactating animals leads to early return to estrous (two months after calving). Msangi et al. (2004) observed that supplementary feeding to crossbreds in early lactation enhanced energy intake and metabolizable energy appeared to be channeled

towards body tissue rather than stimulating increased milk yield. Therefore in the model, supplementation is mainly considered for the improvement of fertility rather than its impact on milk production. In this simulation scenario, the lactation length for crossbred cattle was reduced to 6 months and lactating animals were supplemented with 2 kg of dairy meal to ensure that they conceived in the third month after calving. In this production system, every herd had at least two bulls at all the time (Peloschek, 2009) therefore the inadequacy of bulls as a limiting factor for conception was not considered.

5.2.2 Scenario 2. Optimal stocking density and off-takes

Unlike in previous studies where the herds were evaluated in steady state or fixed stocking rates (Kothmann and Smith, 1983, Díaz-solis et al., 2003), the key unique component of the current model was that simulation considers dynamic stocking rate which changes over a given simulation production year. Mulindwa et al. (2009) reported carrying capacity values for each of the month of the year for the current study area and based on that, a range of stocking rates (0.5, 1, 1.5, 1.75 and 2ha/TLU) were adopted to act as optimum whereby if the stocking rate exceeds the (optimal) maximum stocking rate allowed, the excess (the same proportion of heifers) referred to as capping in (Hahn et al., 2005) was removed and added to off-take. Capping does not mean that the stocking rate is fixed rather it varies but never exceeds the maximum cap value. It is these capping values that were eventually evaluated for economic viability. The different animal cohorts (calves, heifer, cows and steers) that made up the herd were converted to tropical livestock units (TLU) by adopting the conversion factors used by Mulindwa et al. (2009). Apart from determining the off-takes, the model calculated the replacement rate, which was defined as the number of heifers retained at weaning to maintain the cow herd below the predetermined optimal stoking rate.

5.3 Scenario 3. Restricted breeding season

The reproductive performance of dairy herds cannot be considered in isolation from the overall performance of the whole farm system. The efficiency of pasture harvest

and its conversion to milk within the context of the system is influenced by the reproductive performance of the herd as manifested in the herd's calving pattern. The ability to determine the proportion of cows which at an appropriate point in their lactation cycle are able to transfer the energy and protein captured during the period of optimal grass growth into milk production at lactation peak when this process is most energetically efficient is paramount. Thus the shape of the calving pattern (its peak/s and its tail) as well as its temporal position in relation to grass growth (the calendar date on which it begins) will influence the efficiency of the whole farm system. Galukande (2010) reported that month of milk sampling greatly influenced the daily milk yield from the Ankole-Friesian crossbreds. In the current Ankole livestock production system, mating is done by natural service and there is no controlled breeding of the animals. Cows are calving throughout the year. In the study carried out in the same production system Galukande (2010) observed that the majority of the animals calved in the long rain season (March to May) followed by the short rain season (September and October) but a substantial number of animals calved in the dry seasons. Pasture-based systems require a compact calving season and a calving interval of 365 d to ensure that maximum animal demand coincides with peak pasture growth (Dillon et al., 1995). In the current production system, there are two rain seasons through which calving could occur. The performance of the system was evaluated by having only two calving seasons. To ensure this, cows and heifers were divided into two herds, one herd calving in the first rain season and the other in the second rain season. No calving was allowed to take place in the dry season. For the control scenario, calving was allowed to occur throughout the year. The simulated scenario ensures milk production through out the year but at the same time allows animals to calve in the rain season and take advantage of the abundant forage.

5.3 Results and Discussion

5.3.1 Altered open period and lactation length in Ankole-Friesian crossbreds

Results for scenario 1 (reduced lactation length and early conception) are presented in Table 5.1. The average monthly and annual incomes were higher (17.3%) in the control scenario than in the scenario 1. The TLU in the control and scenario 1 was

relatively similar (166.47 vs 166.82) but the herd value of scenario 1 was 23.5% higher than the control group. The difference in herd value (monetary) could be explained by the fact that scenario 1 had relatively more heifers than the control throughout the simulation period (see Figure 5.1). The monetary values of each of the animal class within the herd are presented in Appendix 3. In this production system, Ankole-Friesian crossbred heifers fetch a higher premium (average 414 \$) compared to the rest of the animal cohorts. This kind of undertaking provides an opportunity to pastoralists to produce more heifers which have a ready market provided by the urban smallholder livestock keepers (zero grazing) as well as market from neighbouring Rwanda. When the sum of the average monthly income and herd value for both scenarios are divided by the same denominator, it is clearly seen that scenario 1 is by far more profitable (15.7%) than the control group. The implication of this finding is that pastoralists should concentrate on supplementing their animals during the early stages of lactation that would ensure early conception and hence more calves born over the lifetime of a cow.

Table 5.1 Effect of reduced lactation length and early conception on the gross margin, TLU and Herd value of crossbred herd

Key performance indicator	Management option	
	Control	Scenario 1
Monthly gross margin (\$)	1690 (892)	1397 (1252)
Annual gross margin (\$)	20402 (4530)	16862 (3388)
TLU	166.47 (39.74)	166.82 (39.27)
Herd value (\$)	41309 (8880)	50999 (12056)

Scenario 1 = reduced lactation length and early conception

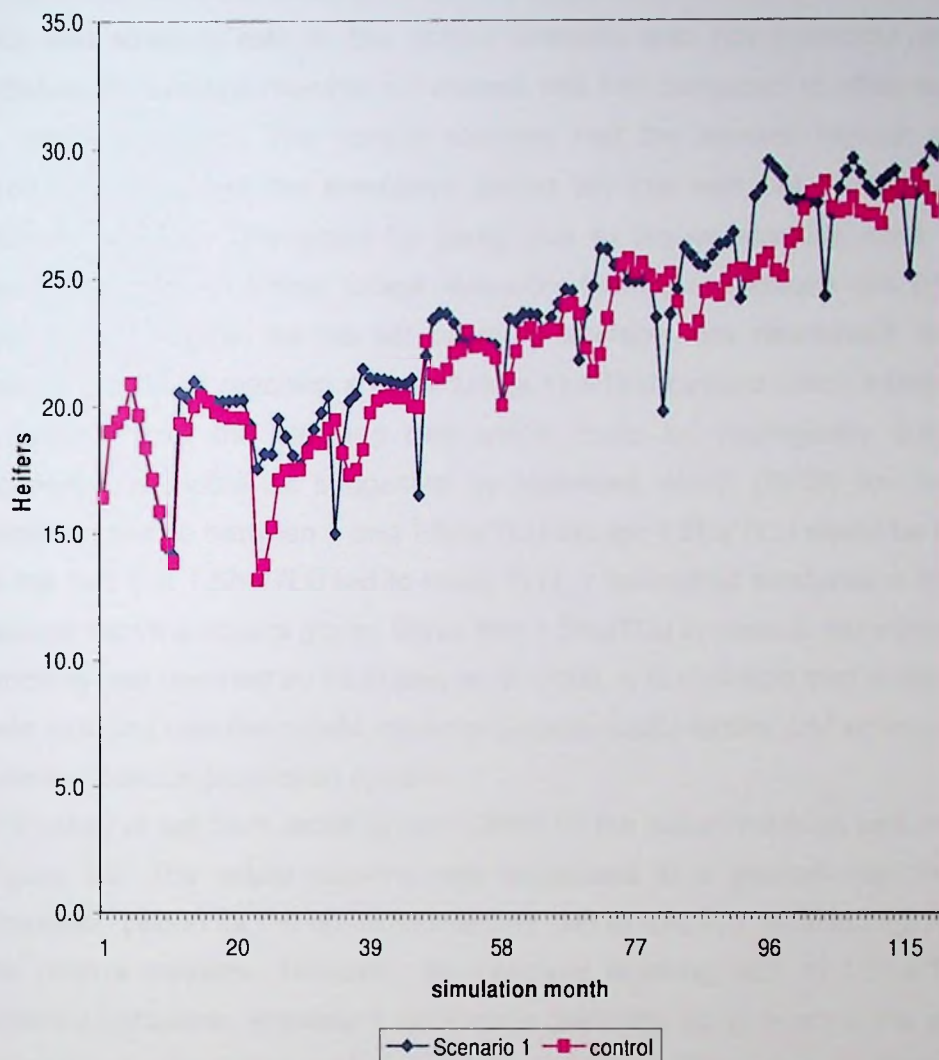


Figure 5.1 Number of heifers over 10 year simulation period

5.3.2 Influence of optimal stocking rate on the monthly net margin

Results on average TLU over 10 year simulation period and the effect of optimized stocking rate (scenario 2) are presented in Table 5.2. The pre-set values of optimum stocking rates used in scenario 2 were based on monthly carrying capacity values reported by Mulindwa et al. (2009). When the optimum stocking rate was set at 2ha/TLU, it produced the least average monthly gross margin (1557\$) followed by

1.75ha/TLU and the stocking rate for the control (1690\$) in that order. Despite the fact that stocking rate in the control scenario was not interfered with (no extra offtakes) its average monthly net income was low compared to other scenarios (0.5, 1, and 1.5ha/TLU). The control scenario had the second highest average TLU (166.47) throughout the simulation period but this was not translated into higher monthly income. This could be partly due to higher stocking rates that lead to competition for the limited forage resources leading to reduced milk production and hence less income. As the set optimum stocking rate decreased, average gross margin increased reaching a maximum at 1ha/TLU beyond which it begun to reduce. It appears that the stocking rate which could be ecologically sustainable and economically viable as suggested by Mulindwa et al. (2009) for this production system could be between 1 and 1.5ha/TLU though 1.5ha/TLU would be ideal. Despite of the fact that 1.5ha/TLU led to lower TLU, it somewhat produces a higher (by 2%) income than the control group. Given that 1.5ha/TLU is close to the minimum required stocking rate reported by Mulindwa et al. 2009, it is probable that it would act as the best stocking rate that would insure ecological sustainability and economic viability of Ankole livestock production system.

The effect of optimum stocking rate (OSR) on the actual stocking rate is presented in Figure 5.2. The actual stocking rate decreases at a gradual rate throughout the simulation period for the optimum stocking rate of 0.5, 1, 1.75 and 2ha/TLU as well as the control scenario. However, the optimum stocking rate of 1.5ha/TLU shows a different behaviour whereby it decreases gradually up to around the sixth year (72 months) of simulation and eventually stabilizes. This kind of behaviour further confirms the earlier theory that for ecological sustainability of Ankole pastoral system, stoking rates should be kept at around 1.5ha/TLU. The implication of these results is that having optimal stocking rate set at 2ha/TLU for this production system would mean that the ecological state of the rangeland would be good but underutilized whereas 0.5ha/TLU would be economically viable but ecologically not sustainable.

Table 5.2 Average monthly gross margin and TLU over 10 years for the selected optimum stocking rates for the Holstein Friesian crossbred herd

	Control (1.2)	Optimum stocking rates (ha/TLU)				
		0.5	1	1.5	1.75	2
Monthly net	1690	1727	1776	1725	1633	1557
margin (\$)	(892)	(901)	(903)	(809)	(752)	(704)
TLU	166.47	167.19	161.45	138.19	127.16	117.88
	(39.74)	(39.95)	(32.11)	(16.51)	(12.11)	(8.94)

Values in bracket represent the standard deviation, TLU= Tropical Livestock Unit

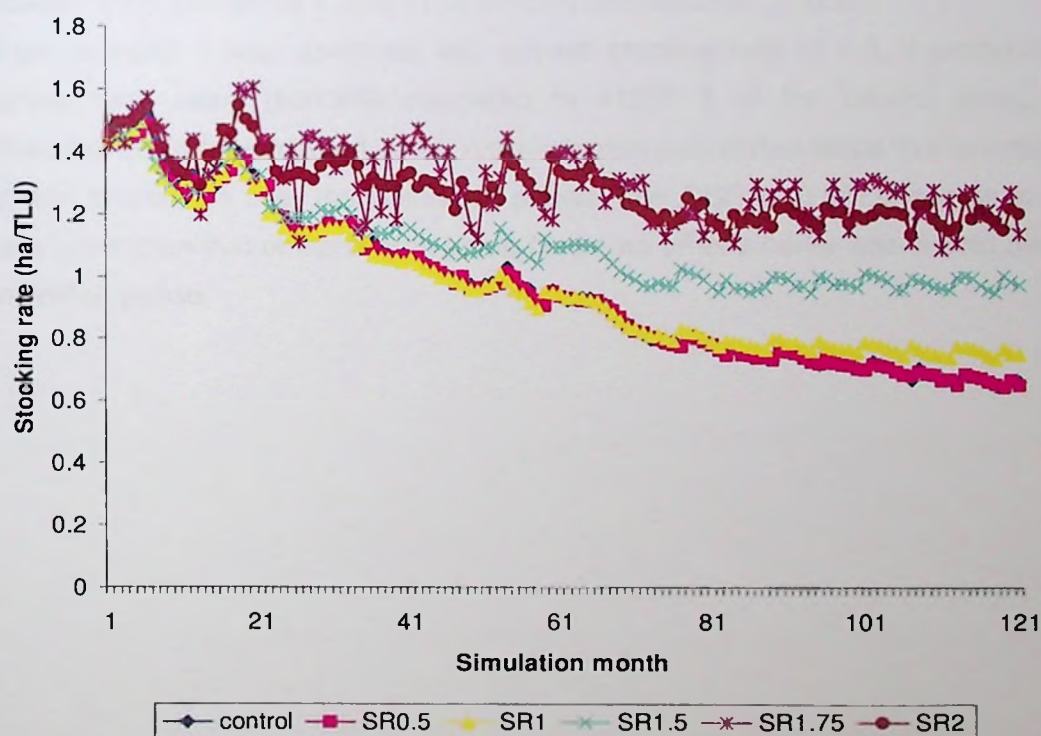


Figure 5.2 Actual stocking rate as influenced by the optimum stocking rate

5.3.3 Use of a combination of altered lactation length and early conception, and optimized stocking rate.

Results for the effect of reduced lactation length and early conception, and optimized stocking rate are presented in Table 5.3. When scenario 1 and 2 were simulated together, the optimized stocking rate set at 2(ha/TLU) resulted in the least average monthly gross margin followed by 0.5(ha/TLU). The control scenario resulted produced the highest gross margin. The behaviour (trend) of the monthly gross margin in simulation scenario 3 is similar to scenario 2 though the magnitudes are generally much higher in scenario 2 (cf. Table 5.2). The overall TLU over the 10 year simulation period reduced as the pre set optimum stocking rate increased from 0.5 to 2ha/TLU. When TLU values in Scenario 2 are compared with those of Scenario 3 in their respective OSR, it appears that there is a very small marginal difference between them except for 1.5(ha/TLU) which a difference of 11TLU.

When scenario 1 was combined with optimal stocking rate of 0.5, it produced the highest herd value (69036\$) compared to 41309 \$ of the control group. The difference could be attributed to the reduced open period that leads to the increased number of animals over the simulation period. The OSR of 0.5TLU seems to have been lower than that of the control group hence no offtake heifer where sold over the simulation period.

Table 5.3 Average monthly gross prifit and TLU over 10 years for the selected optimum stocking rates, and reduced lactation length and early conception for the Holstein Friesian crossbred herd

	Control 1.2)	Scenario 1 and Optimum stocking rates(ha/TLU)/				
		0.5	1	1.5	1.75	2
Monthly gross	1690	1384	1451	1415	1355	1296
profit (\$)	(892)	(1246)	(1275)	(1193)	(1147)	(1086)
TLU	166	167	159	127	126	116
	(39.74)	(39.27)	(31.17)	(13.24)	(12.87)	(10.09)
Herd value (\$)	41309	69036	48221	37746	53432	49599

Scenario 1= reduced lactation length to six months and open period set at 3 months

5.3.3 Impact of restricted breeding season

Results on the performance of the crossbred herd when breeding was restricted are presented in Table 5.4. The average monthly net income, milk income and annual net income were higher (24%, 36%, 23% respectively) in the restricted breeding scenario than in the control group. The high standard deviations for the monthly net income are a result of the great variation in monthly income of the farms. This is because culling of old animals is done in specific months such as May (prior to long dry season) and November (to take advantage of the high prices presented by the festive season) which led to higher incomes compared to other months. The increased high net income in the restricted breeding scenario is partly due to the higher daily milk yields as demonstrated in Figure 5.3. When the daily milk yield for the two scenarios was analyzed using a general linear model of (SAS, 2008) in which simulation year and breeding type were considered as fixed effects, including the stocking rate as a covariance (Appendix 2), the restricted breeding scenario was 0.3kg of more than the year round simulation. The TLUs in the restricted breeding scenario were more (22 TLU) than in the control group. The difference could be due to the methods used in achieving conception of the animals after calving. In the base model (control) the

open period was achieved randomly and the length varied between 2 and 6 months whereas in the restricted breeding scenario, open period was set at 3 months after calving. Allowing cows and heifers to calve in any month of the year meant that some of them calved in the hostile dry period which affects their milk production performance and body condition leading to delayed return to estrous. Single breeding seasons are being practiced in the temperate climates and also other areas like New Zealand but such a breeding practice leads to a period with in the year when there is no milk production after drying off all the animals. In the Ankole pastoral system, such a practice would impair the livelihood of livestock keepers since pastoralists greatly depend on the daily income from milk sales. Restricted breeding is feasible in Ankole pastoral system and not only does it increase milk yield but also has other benefits reported in studies elsewhere (Khonje et al. 1992) in which cows that calved in the hot wet season had a shorter calving interval, shortened pre-weaning calf mortalities as well as shortened periods from calving to first oestrus, and calving interval. In the restricted breeding scenario, the herd value increased on average by 3% in relation to the control group Table 5.4.

Table 5.4 Restricted breeding effect on gross profit, TLU and herd value of crossbred herd

	Control	Scenario 4
Monthly net income (\$)	1690 (892)	2106(1656)
Monthly milk income (\$)	968 (260)	1312 (770)
Annual net income	20402 (4530)	25287 (4347)
TLU	166 (39.74)	188(47.02)
Herd value (\$)	41309 (8880)	42469(5467)

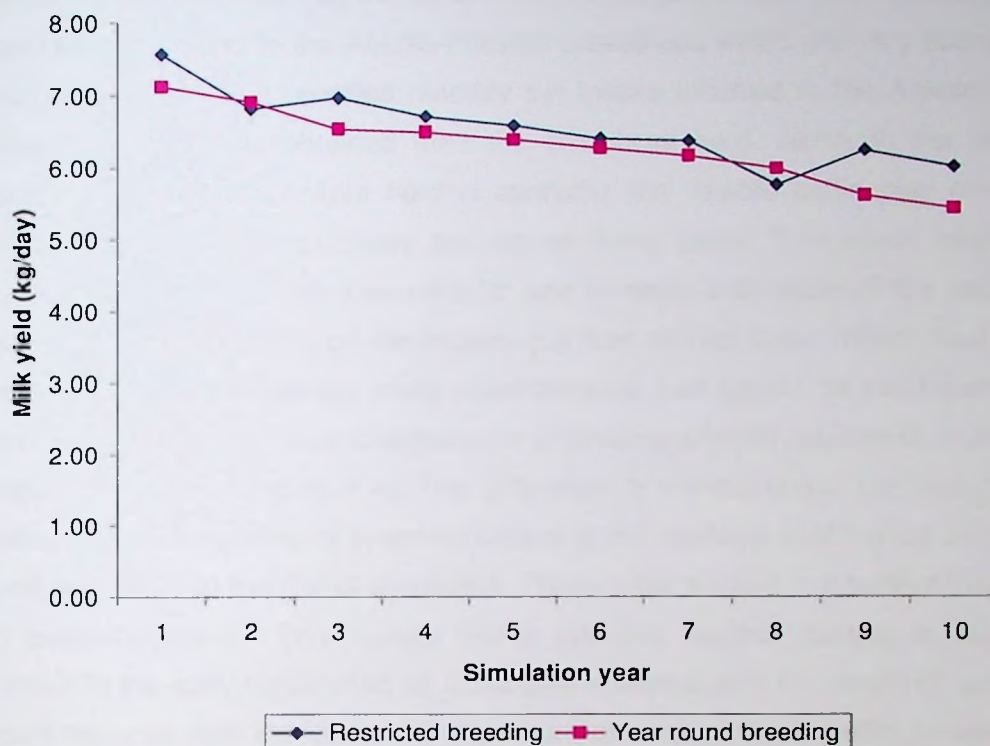


Figure 5.3 Impact of restricted seasonal breeding on daily milk yield (kg/day)

5.3.4 Impact of reduced open period on Ankole herd

Like in the crossbred herd, the impact of reduced open period on the monthly income in the Ankole herd was evaluated and the results are presented in Figure 5.3. It is evident that reduction of open period of Ankole cattle has got a minimal contribution to the monthly income. The simulations indicate that in a substantial number of months, the Ankole herd is operated on net losses. Net incomes are only realized in those months when some yearling (steers) and old cows are sold. The high costs are mainly contributed by the weekly spraying of cattle against East coast fever (cattle disease of most economic importance in the tropical Sub-Saharan Africa). Although the Ankole cattle are largely reported to be resistant to East coast fever (ECF) (Paling et al., 1991, Ocaido et al., 1996), livestock keepers are forced to spray them regularly

due to the fact that they may act as carriers of ticks (the vector for the pathogens) that could be transmitted to the Ankole-Friesian crossbreds which are very susceptible to East coast fever. The reported monthly net losses incurred in the Ankole herd are offset by the income obtained from the crossbred herd. Although the household monthly income from Ankole herd is sporadic, the Ankole cattle play other social functions like payment of dowry and act as living banks from which cash can be raised through sales. This also calls for an in-depth evaluation of the value of the herd rather than focusing on the income got from animal sales. When analysing the profile of the herd, there are some characteristics that should be mentioned. As the herd was developing, other categories of producing animals appeared, changing the profile of the herd (Figure 5.4). The difference of control group and reduced open period scenario in terms of pregnant heifers is not realized until for example the number of after 40 months of simulation. The number of pregnant heifers increased in an oscillation form. This means that a livestock keeper starting to supplement animals in the early lactation so as to achieve a decrease in the length of open period would have to wait for at least three years to realize the benefits in terms more animals.

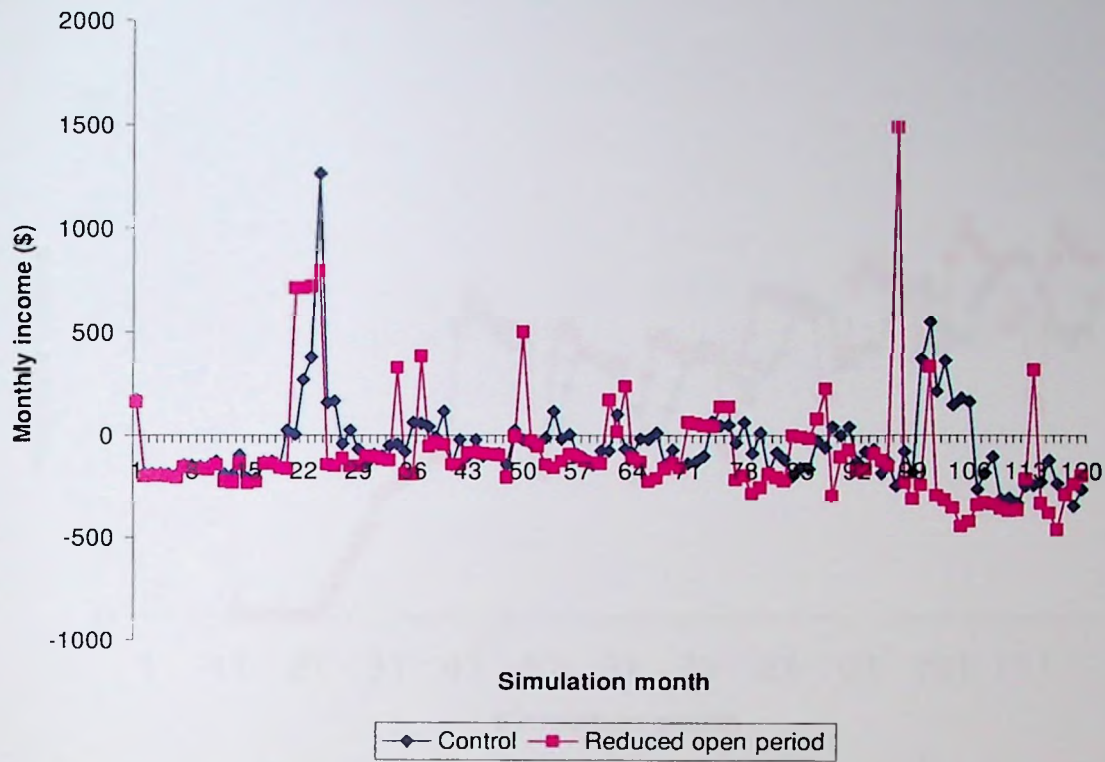


Figure 5.4: Monthly income for the Ankole herd

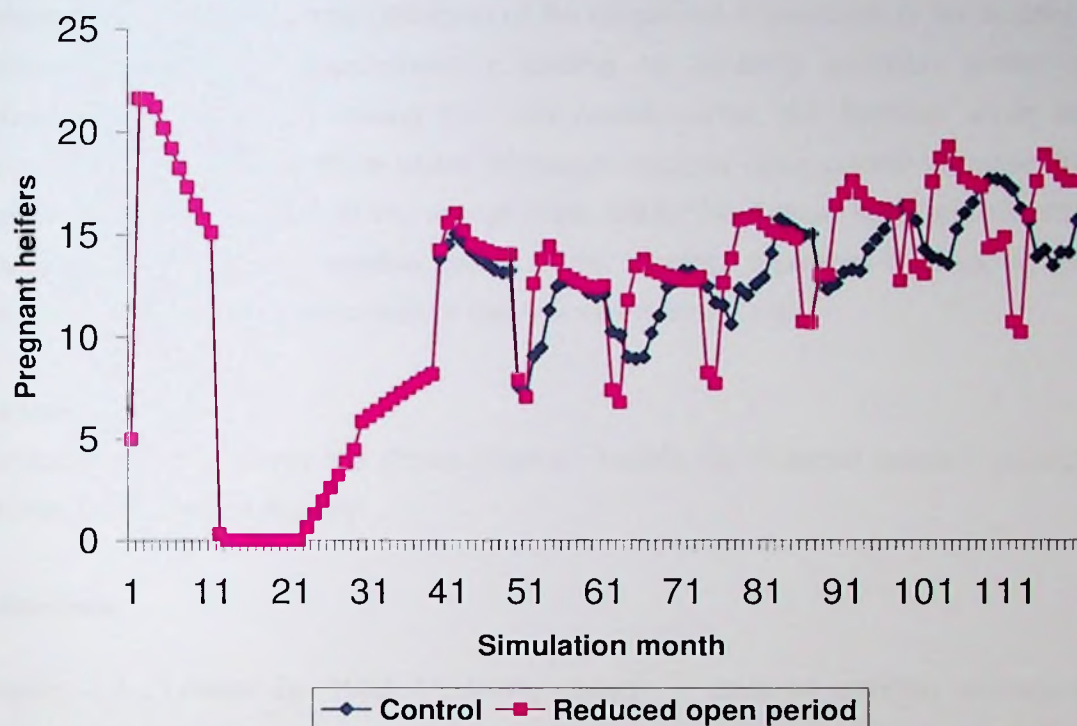


Figure 5.5 Profile of Ankole pregnant heifers during the simulation

5.4 Conclusions

The complex long-term simulation experiment was used to estimate the financial performance of specified alternative management options, measured as net profit per year or per month. The simulations demonstrated that restricted breeding season was considerably more profitable and had a higher turnover than all year round breeding; indicating that the two existing rainy seasons can be used as calving seasons to enhance profitability and high herd value. Restricted breeding increased daily milk production by 0.3kg. The stocking rate that is ecologically sustainable and economically viable for Ankole pastoral production system has been found to be

around 1.5 ha/TLU. A stocking rate below 1 ha/TLU is economically viable but ecologically unsustainable whereas a stocking rate above 2 ha/TLU is ecologically sustainable but leads to under utilization of the rangeland. If pastoralists are to adopt management methods (supplementary feeding of lactating animals) aimed at reducing the open period among the pure Ankole cattle, the benefits would be realized after a period of three years. Although reduced open period increase the number of animals in each of the animal class within the Ankole herd, the monthly income largely remained negative. Much of the monthly expenses incurred in the Ankole herd are offset by income from the Ankole-Friesian cattle.

Acknowledgment

The authors acknowledge the Government of Austria for financial support through Austrian Development Agency.

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CHAPTER VI

6.0 General discussion

In one of the studies, a survey was carried out with the aim of generating information about farmers' awareness of the state of their range and how they have applied their indigenous knowledge in the utilisation of their rangelands. The study revealed that farmers' perception and interpretation of indicator plant species was important for allocation of the various parts of the household rangeland to the different cattle genotypes. Medium or high quality graded areas were largely allocated to Ankole-Friesian crossbred cattle while those considered as low quality were allocated to pure Ankole cattle. In addition, Ankole cattle were allocated pastures located far from homesteads and water sources. The above decision indicates that farmers are aware of the good and bad attributes of either cattle genotype. For instance, Ankole cattle are known for being hardy and capable of trekking long distances hence the decision to graze them away from water sources while the Ankole-Friesian crossbreeds known to be susceptible to hot temperature and can hardly walk long distances are grazed near homesteads with the intention of giving them quick attention when needed. Although subjective, farmer's assessment of their pasture in terms of quality and quantity concurred with laboratory analysis. The livestock keepers possess immense knowledge about traditional forage species which they ably identified and hence there is a need to involve them in the promotion of fodder production based on the species they identified as "good" and confirmed by laboratory tests. The most important plant species as identified by farmers were *Hyparrhenia rufa*, *Brachiaria spp*, *Themeda triandra* and *Chloris gayana*. The most common unwanted species were *Sporobolus pyramidalis* and *Cymbopogon afronardus*. Possibly the greatest obstacle to improving Ankole pastures is the low priority farmers place on pasture concerns relative to livestock husbandry. Apart from clearing weeds, there is limited effort towards proper use of the rangeland. It is recommended that any pasture development program should focus on those species that are adapted to the area and which farmers are familiar with and have confidence in. Given its quick growth response to rains, high herbage yield, and susceptibility to drought, *Brachiaria spp* could be strategically used for making hay to be fed as supplement during dry season. Hay making could be

done in the early stages of the rain season during which time *Brachiaria spp* are in abundance. The study revealed that plant species considered as "good" by farmers have been gradually reducing over time and those considered as "bad" were on the increase. The above trend could be partly attributed to the high stocking densities that were later identified on the selected farms coupled with selective grazing tendency of cattle where "good" pasture species are grazed more compared to the "bad" pasture species. It was also discovered that little paddocking was taking place in this production system which indicates inefficiency in the utilization of the available forage. Currently pastoralists use herdsmen to guide the cattle to the different grazing areas but this practice is not as effective as paddocks and a decline in the availability of labour, reported by farmers, is gradually increasing as more and more young people go to school and look for other lucrative jobs other than working as herdsmen. Although it requires a substantial amount of investment, one of the first steps of introducing new technologies on these farms should be the use of rotational grazing by use of small sized paddocks which allow the pasture to be more efficiently grazed. Pastoralists reported presence of soil erosion on their farms, an indicator of overgrazing. This study has found that 63% of the farmers were found to overgraze throughout the year while 37% overgraze during the dry season. Overgrazing adversely effects soil properties such as reduced infiltration and accelerated runoff leading to soil erosion. There has been scanty information about the carrying capacity (CC) of the Ankole rangelands and the available figures were based on single year studies and yet Ankole rangelands are semi-arid and experience a lot of seasonal rainfall variability therefore the CC values obtained from a single year can be either over estimated or underestimated depending on the amount of rainfall in the study year. Stochastic simulation was used to simulate rainfall data covering several years to eliminate bias in the results. The CC for Ankole rangelands was found to be dynamic and its variability was more pronounced within the year than between years. Although big short term changes to stocking rates may not be possible the major point of intervention to reduce stocking rates could be done in May, shortly before the start of long dry season. Based on the results of this study, for the Ankole pastoral system to be sustainable, the stocking rate should not go below 1.41ha/TLU

(0.71TLU/ha). It is also important that the grazing capacity of the Ankole rangelands is estimated through continuous monitoring and evaluation.

The study developed a stochastic dynamic simulation model for the Ankole pastoral system that was then used to evaluate some alternative management options. The model was written in STELLA software and much focus was put on the elements of the pastoral system that are essential to the biological herd dynamics (population sex and stage structure, and the observed vital rates) and the management decisions as dictated by the breeding system, and social economic factors. The evaluation of the model against field data showed that it could be used in evaluating some strategic and tactical management options of the grazing system in South Western Uganda. However, the model needs to be validated using other model parameters and field data from other farming systems with similar climatic conditions before it can be used on a wider scale. Usually the purpose of model validation for any model is not to prove that the model is truthful, but rather to build confidence in the design and implementation of the model. Due to lack of comprehensive experimental data, some realistic assumptions were made based on the research done elsewhere and consultations with experts. Overall, the evaluation approaches used addressed the internal and external consistency of the model. One of the weaknesses of the model was its failure to simulate conception of animals based on the nutrition status of the animals. As more experimental data become available, estimation equations can be modified so that a more comprehensive model is developed to describe the effect of stocking density on forage production, forage composition and quality from year to year for a given livestock grazing pattern. The developed model also provides a framework for conducting further research and there is a possibility of using it as a starting point to the development of a decision support system to enhance livestock management decisions of the pastoralists and give more informed guidance to policy makers.

Computer simulation has the potential to improve dairy (and other) farming practices without the need to physically test enormous numbers of different strategies. One problem for pastoralists is that it is difficult to determine whether a farm with no obvious problems is as good as it can get, or whether there exists a different

management scheme which would provide more profit or improve the quality of his/her cattle herd structure.

The stocking rate that is ecologically sustainable and economically viable for Ankole pastoral production system has been found to be around 1.5ha/TLU. A stocking rate below 1ha/TLU is economically viable but ecologically unsustainable whereas to a stocking rate above 2ha/TLU is ecologically sustainable but leads to under utilization of the rangeland. The major challenge lies ahead to convince pastoral people about the benefits of using optimal stocking rates and improving production efficiencies, in order to achieve higher livestock production, an improvement in income and less degradation of the rangeland.

Restricted breeding led to an increase in milk production of about 0.3kg/day. The magnitude of milk increase may appear small but when considered on the herd level, it translates into a substantial amount of income. It has been discovered that having short lactations of 6 six months and accompanied by the supplemental feeding (first two months of lactation) to the lactating cows is more profitable than having long lactations (8 months) without supplemental feeding. The costs incurred on supplements (dairy meal) can be recovered due to the overall higher performance of the herd as a result of more calves being born within a year.

With human population continuously increasing coupled with gradual increase in the general standard of living in Uganda and high demand for milk products, continued crossbreeding in the Ankole livestock production systems is inevitable, especially in this area where alternative employment opportunities are limited and livestock is major source of livelihood for family members. The success of keeping the two genotypes on the same farm will depend on the fact that pastoralists realize that each cattle genotype has different characteristics and requires changes in cattle management practices ranging from feeding, pattern of breeding, disease and number of animals kept on a particular farm. It is worth noting that livestock keepers in this area have already embraced change such as the selective allocation of cattle genotypes to specific rangeland areas, and regular spraying of Ankole pure cattle, something that was never done before crossbreeding was started. More cattle husbandry changes are still needed such as improved pasture management and

timing of breeding animals and control of cattle numbers. Efforts to improve the efficiency of the emerging production system need to be facilitated by stronger institutions, local empowerment and regulation of access to resources. The local government, scientists, extension workers, and farmers themselves have to work together, because improving livestock production means that pastoralists need access to reliable and affordable support services, offering them access to knowledge, inputs, marketing information as well as credit that would especially facilitate the establishment of paddocks which are much needed in order to enhance the efficient utilization of forage resources.

The study has revealed that keeping both cattle genotypes in close proximity on the same farm leads to incurring more costs (Acaricide costs) for the Ankole cattle herd which would otherwise have been avoided had the pastoralists been keeping pure Ankole cattle completely separate from the crossbreds without sharing facilities like watering sources and crushes. The crossbreeding strategy is economically viable even without support from proceeds obtained from the sale of pure Ankole cattle and could be sustained by use of Ankole-Friesian composite bulls without necessarily producing crossbreds from mating Holstein Friesian bulls with Ankole cows to produce crossbreds.

Any intervention however should not have an adverse effect on the social benefits pastoralists get from the pure Ankole cattle. It is recommended that on-farm pilot livestock projects should be established in the Ankole pastoral production area to demonstrate the feasibility of the higher benefits from the management strategies identified in this study.

Summary

The Bahima ethnic group of South Western Uganda formerly kept exclusively Ankole cattle but has recently begun crossbreeding pure Ankole cattle with Holstein Friesian bulls. Separate herds consisting of pure Ankole and crossbred animals are common. Given the complexity presented by the emerging production system as well as the well documented problems usually faced by crossbreds between temperate breeds and tropical indigenous cattle, a study was undertaken to evaluate the long term productivity of the emerging production system, identify its constraints and evaluate some alternative management options. Sixteen farms were selected and data on a number of parameters were collected. The study revealed that the pastoralists were largely carrying out continuous grazing with minimal use of paddocks. *Hyparrhenia rufa*, *Brachiaria spp*, *Themeda triandra* and *Chloris gayana* were identified as the most important pasture species whereas *Sporobolus pyramidalis* and *Cymbopogon afronardus* were the most unwanted plant species. Presence of high quality feed (80%), limited shrubs/weeds (80%) and close proximity to the homestead (30%) were the main factors considered when allocating cattle genotypes to their respective grazing landscapes. Crossbred cattle were kept on medium or high quality pastures whereas Ankole cattle were mostly kept on medium and low quality pastures. Crossbred pasture had 0.17t/ha DM more than the range grazed by pure Ankole cattle. The CP content in pastures grazed by pure Ankole (6.30%) was significantly ($P<0.05$) lower compared to Ankole-Friesian crossbred grazed range (7.25%). NDF content was relatively similar (72.82% vs. 69.77%) in both range types. The presence of *Brachiaria spp* in the range offers an opportunity for being utilized as hay for feeding as supplement during dryseason. Using a stochastic dynamic simulation model the dynamics of pastures grazed by Ankole cattle and their Holstein Friesian crosses and the carrying capacity (CC) of the livestock grazing system was determined. The overall annual forage production is $3905 \pm 72\text{kg/ha}$. The lowest CC ($5.65 \pm 0.75\text{ha/TLU}$) occurs in long dry season (June to August) while the highest CC ($1.41 \pm 0.06\text{ha/TLU}$) occurs in short rain season (September to November). Annual carrying capacity ranges between 1.88 and 2.08ha/TLU with an overall mean of $1.95 \pm 0.04\text{ha/TLU}$. Sixty three percent of the surveyed farms have stocking rates that are

higher than the CC throughout the year while the rest are overstocked in the dry seasons of the year. The results indicate that CC is dynamic and its variability is more pronounced within the year than between years. The major point of intervention in regard to reduction of actual stocking rates could be done in May shortly before the start of the long dry season. For Ankole pastoral system to be sustainable, the stocking rate should not go below 1.41ha/TLU.

A comprehensive dynamic simulation model of Ankole pastoral system was developed to provide a tool for developing and testing alternative management options for their economic viability and ecological sustainability. The model linked climate information with dynamic stochastic sub-models for pasture growth, animal production and economic as well as farmers' management policies. The model outputs were compared with field data collected over 3 years. The relative prediction error (RPE) values for body weight after weaning (7 to 18 months) across both breeds ranged from 3% to 12% which is below the acceptable limit of 20% and means that the model predicts post weaning growth with an average error of 7.5%. The model predicted pasture production and milk yield across seasons with relative prediction errors of 17.6% and 3.33% respectively. The graph shapes of actual and predicted average daily milk yield as influenced by season (month of the year) were similar. Because pasture growth and milk production predictions were acceptable, economic projections can be made using the model to test different alternative management options. Using the above model, alternative management options were evaluated that included reduction on open period and shorter lactation length (1), optimum stocking rates (2) and restricted breeding season (3). Economic analyses were conducted for each of the options and some of their combinations. In scenario 1, the average monthly and annual incomes were higher by 17.3% in the control scenario than in the scenario 1. Though both scenario 1 and control group had relatively similar average TLU, the herd value of scenario 1 was 23% higher than the control group. In scenario 2, the optimal stocking rate set at 1.5ha/TLU had a higher (by 2%) income compared to the control group even though average stocking rate was less by 28.28TLU. Daily milk yield in the Ankole-Friesian crossbred herd was generally higher (0.3kg) in the restricted breeding scenario than the year round breeding. The reduction in the open

period length for the Ankole herd marginally improved the monthly gross income compared to the control group but both scenarios resulted in monthly net losses with exception of a few months when more animals were sold. Adoption of restricted breeding season would substantially improve the efficiency of the production system due to more milk harvest as well as improved quality of the herd. The stocking rate that is ecologically sustainable and economically viable for Ankole pastoral production system has been found to be around 1.5ha/TLU. A stocking rate below 1ha/TLU is economically viable but ecologically unsustainable whereas to a stocking rate above 2ha/TLU is ecologically sustainable but leads to under utilization of the rangeland. If pastoralists are to adopt management methods aimed at reducing calving interval among the pure Ankole cattle, the benefits would be realized after a period of three years. Overall, the crossbred herds are much more economical than the pure Ankole herds. Pastoralists are recommended to drastically reduce the herd sizes for Ankole herds and only keep small numbers to address the social benefits (payment of dowry).

Appendix 1: Model equations used in chapter 3.

MRAIN = RANDOM (0, 1)

Janrain = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.292) then 16 else if (MPPT_RF<0.625) then 45 else if (MPPT_RF<0.854) then 75 else if (MPPT_RF<0.958) then 105 else if (MPPT_RF<1) then 135 else 0

Febrain = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.191) then 16 else if (MPPT_RF<0.595) then 45 else if (MPPT_RF<0.808) then 75 else if (MPPT_RF<0.957) then 105 else if (MPPT_RF<1) then 135 else 0

Marrain = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.021) then 16 else if (MPPT_RF<0.191) then 45 else if (MPPT_RF<0.489) then 75 else if (MPPT_RF<0.787) then 105 else if (MPPT_RF<0.915) then 135 else if (MPPT_RF<1) then 165 else 0

Aprirain = if (MPPT_RF<0.01) then 0 else if (MPPT_RF<0.043) then 30 else if (MPPT_RF<0.298) then 75 else if (MPPT_RF<0.553) then 105 else if (MPPT_RF<0.808) then 135 else if (MPPT_RF<0.914) then 165 else if (MPPT_RF<0.978) then 195 else if (MPPT_RF<1) then 225 else 0

Mayrain = if (MPPT_RF<0.021) then 0 else if (MPPT_RF<0.212) then 16 else if (MPPT_RF<0.446) then 45 else if (MPPT_RF<0.68) then 75 else if (MPPT_RF<0.871) then 105 else if (MPPT_RF<0.977) then 150 else if (MPPT_RF<1) then 195 else 0

Junrain = if (MPPT_RF<0.065) then 0 else if (MPPT_RF<0.695) then 16 else if (MPPT_RF<0.847) then 45 else if (MPPT_RF<0.912) then 75 else if (MPPT_RF<1) then 150 else 0

Julrain = if (MPPT_RF<0.087) then 0 else if (MPPT_RF<0.478) then 8 else if (MPPT_RF<0.674) then 23 else if (MPPT_RF<0.761) then 38 else if (MPPT_RF<0.848) then 53 else if (MPPT_RF<0.935) then 68 else if (MPPT_RF<1) then 83 else 0

Augrain = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.196) then 16 else if (MPPT_RF<0.5) then 45 else if (MPPT_RF<0.761) then 75 else if (MPPT_RF<0.87) then 105 else if (MPPT_RF<0.935) then 135 else if (MPPT_RF<1) then 165 else 0

Septrain = if (MPPT_RF<0.01) then 0 else if (MPPT_RF<0.022) then 16 else if (MPPT_RF<0.222) then 45 else if (MPPT_RF<0.442) then 75 else if (MPPT_RF<0.732) then 105 else if (MPPT_RF<0.91) then 135 else if (MPPT_RF<1) then 165 else 0

Octrain = if (MPPT_RF<0.04) then 0 else if (MPPT_RF<0.065) then 30 else if (MPPT_RF<0.195) then 75 else if (MPPT_RF<0.521) then 105 else if (MPPT_RF<0.738) then 135 else if (MPPT_RF<0.825) then 165 else if (MPPT_RF<0.912) then 195 else if (MPPT_RF<0.977) then 255 else if (MPPT_RF<1) then 285 else 0

Novrain = if (MPPT_RF<0.02) then 0 else if (MPPT_RF<0.043) then 30 else if (MPPT_RF<0.239) then 75 else if (MPPT_RF<0.435) then 105 else if (MPPT_RF<0.674) then 135 else if (MPPT_RF<0.848) then 165 else if (MPPT_RF<0.957) then 195 else if (MPPT_RF<0.979) then 225 else if (MPPT_RF<1) then 255 else 0

Decrain = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.114) then 16 else if (MPPT_RF<0.387) then 45 else if (MPPT_RF<0.728) then 75 else if (MPPT_RF<0.91) then 105 else if (MPPT_RF<0.955) then 150 else if (MPPT_RF<0.978) then 195 else if (MPPT_RF<1) then 225 else 0

MRF = if (months = 1) then (Jan rainfall) else if (months = 2) then (Feb rainfall) else if (months = 3) then (Mar rainfall) else if (months = 4) then (Apr rainfall) else if (months = 5) then (May rainfall) else if (months = 6) then (June rainfall) else if (months = 7) then (July rainfall) else if (months = 8) then (Aug rainfall) else if (months = 9) then (Sept rainfall) else if (months = 10) then (Oct rainfall) else if (months = 11) then (Nov rainfall) else if (months = 12) then (Dec rainfall) else 0

Months = COUNTER (1, 13)

Document: Month of the year (1= January, 12= December)

Gr = MRF * RUE

Document: Monthly forage growth rate (kg/ha/month)

Season available forage = IF (Months=3) OR (Months=6) OR (Months=9) OR (Months=12) THEN (SFP*0.3) ELSE (0) (kg)

SFP = IF(Months=3) THEN(GF) ELSE IF (Months=6) THEN(GF) ELSE
IF(Months=9)THEN (GF) ELSE IF(Months=12) THEN(GF)ELSE(0) (kg/ha)

Document: Seasonal forage production

$GF(t) = GF(t - dt) + (Gr - SFP) * dt$

INIT GF = 0 (kg)

Document: Monthly forage production

Annual available forage = IF (Months = 12) THEN (ANFP * 0.3) ELSE (0) (kg/year)

Season carrying capacity = IF (Months=3) OR (Months=6) OR (Months=9) OR
(Months=12) THEN ((Forage demand/ TLU/ day *90)/Season Available forage) ELSE
(0) (ha/cow)

Annual Carrying capacity = IF (Months = 12) THEN (Forage demand per TLU/day *
365) /Annual available forage) ELSE (0) (ha/TLU)

Forage demand/ TLU/ day = TLU body weight * 0.025

Document: Forage demand per TLU per day (kg/day)

Tropical Livestock Unit = 250 kg

RUE = 4 (kg/mm/year)

Appendix 2: Analysis of variance and LSmeans of daily milk yield of restricted breeding scenario and year round breeding for the crossbred herd

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Simulation year (SY)	9	7.27576186	0.80841798	0.87	0.5516
Breeding type (BT)	1	2.63049826	2.63049826	2.84	0.0937
SY*BT	9	3.26757968	0.36306441	0.39	0.9385
Stocking rate	1	4.14963828	4.14963828	4.47	0.0356

**The GLM Procedure
Least Squares Means**

Simulation year	Milk LSMEAN	Standard Error
1	5.69849724	0.60049102
2	6.21033011	0.39812388
3	6.30986490	0.30829130
4	6.36249955	0.24083411
5	6.34233427	0.19979504
6	6.45228573	0.20978863
7	6.55677024	0.25424753
8	6.57815489	0.32563029
9	6.37603919	0.38590153
10	6.19547343	0.44514128

Breeding type	Milk LSMEAN	Standard Error
Restricted breeding	6.49759520	0.12220576
Year round breeding	6.11885470	0.13572303

Appendix 3: Cost s of inputs and prices of various categories of cattle

Input/ output	Cattle genotype	
	Ankole	Ankole-Friesian Crossbred
Acaricide per month (\$)	28	40
Drench (\$)	26	48
Drug expenditure (\$)	35	115
Labour cost (\$)	49	133
Mineral (\$)	22	35
Old cows price (\$)	303	334
Heifer price (\$)	205	414
Young bulls price (\$)	91	101
Calves price (\$)	26	34

Appendix 4: Equation used in the model arranged in order of execution

```
{STELLA VERSION 9.0.2}
{INITIALIZATION EQUATIONS}
Growth_period = 17 {month}
gestationh7 = 7 {months}
Weaning_age = 7 {month}
growth_period_2 = 5 {month}
Min_open_months = 2 {months}
max_open_months = 5 {months}
Months_open = RANDOM (Min_open_months, max_open_months) {months}
DOCUMENT: Open period length
Par_5_cows = 2 {cows}
DOCUMENT: Initial number of cows in parity 5
Cow_mortalityrate = 0.065/12 {cows}
DOCUMENT: mortality rate of cows
gestationh78 = 1 {months}
gestationheifer893 = 1 {months}
PregHeifers7 = 8 {cows}
DOCUMENT: Initial number of heifers in the first 7 months of pregnancy
Par_1 = 7.3 {cows}
DOCUMENT: Initial number of cows in parity 1, lactating but not pregnant
Weaned_heifer_calves = 0 {cows}
DOCUMENT: Initial number of weaned heifers
pregHeifers78 = 0 {cows}
DOCUMENT: Initial number of heifers in the first 8th month of pregnancy
Female_calves = 21 {cows}
DOCUMENT: Initial number of female calves
Weaned_males = 0 {cows}
DOCUMENT: Initial number of weaned calves
Male_calves = 14 {cows}
```

Par_2_cows = 5{cows}

DOCUMENT: Initial number of cows in parity 2, lactating but not pregnant

preg_par1 = 2 {cows}

DOCUMENT: Initial number of cows in parity 2, lactating and pregnant

Dry_par12 = 3 {cow}

Dry_par11 = 0 {cows}

DOCUMENT: Initial number of dry cows in parity 1 the first 8th months of pregnancy

Preg_par_2 = 5 {cows}

DOCUMENT: Initial number of pregnant cows in parity 2 and pregnant

Dry_par_22 = 1{cows}

DOCUMENT: Initial number of dry cows in parity 2 and in last month of pregnancy

Dry_par21 = 0 {cows}

DOCUMENT: Initial number of dry cows in parity 2 and in 8th month of pregnancy

Par_3_cows = 3 {cows}

DOCUMENT: Initial number of lactating cows in parity 3 and not pregnant

preg_par_3 = 4 {cows}

DOCUMENT: Initial number of lactating cows in parity 3 and in early pregnancy

Dry_par_31 = 2 {cows}

DOCUMENT: Initial number of dry cows in parity 3 and 8th month of pregnancy

Par_4_cows = 3 {cows}

DOCUMENT: Initial number of dry cows in parity 4 and lactating but not pregnant

Drypar32 = 0 {cows}

DOCUMENT: Initial number of dry cows in parity 3 and in last month of pregnancy

Preg_par_4 = 4 {cows}

DOCUMENT: Initial number of cows in parity 4 and in the early stage of pregnancy

Dry_par_42 = 2 {cows}

DOCUMENT: Initial number of dry cows in parity 4 and in last month of pregnancy

dry_par_4 = 0 {cows}

DOCUMENT: Initial number of dry cows in parity 4 and in 8th month of pregnancy

preg_par_5 = 1 {cows}

DOCUMENT: Initial number of cows in parity 5 and in early stage of pregnancy

Dry_par_52 = 1 {cows}

DOCUMENT: Initial number of dry cows in parity 5 and in last month of pregnancy

Dry_par_5 = 0 {cows}

DOCUMENT: Initial number of dry cows in parity 5 and in early stage of pregnancy

Par_6_cows = 9 {cows}

DOCUMENT: Initial number of lactating in parity 6 and in not pregnant

preg_par_6 = 4 {cows}

DOCUMENT: Initial number of lactating and pregnant cows in parity 6

pregheifers893 = 0 {cows}

DOCUMENT: Initial number of heifer and in last month of pregnancy

Months = COUNTER (1, 13)

DOCUMENT: Month of the year (1= January ...12= December)

MSmilk = IF (MOL<9) THEN (MOL) ELSE (0)

PKY = 25 {litre}

IRC = 1/ (PKY*0.5*2.718281828)

PMY1 = MSmilk/ (IRC*EXP (0.5*MSmilk))

MILKFat = 3.5

Document: percent milk fat content in milk (Ankole cattle 5.3 % and Crosses 3.5%)

FCM = (0.4*PMY1) + (15*(MILKFat/100)*PMY1) {kg/day}

BWLact = 340 {kg}

DMILact = (0.1*FCM+0.025*BWLact)*30.4 {kg DM/month}

Totlact_nonpreg =

(Par_1)+(Par_2_cows)+(Par_3_cows)+(Par_4_cows)+(Par_5_cows)+(Par_6_cows)
{cows}

TDMILact = DMILact*Totlact_nonpreg {kg DM/month}

BW_yearlings = 150 {kg}

GFDMD = IF(months =1) THEN (0.6874) ELSE IF (months = 2) THEN (0.6698) ELSE
IF(months =3) THEN (0.6584) ELSE IF(months = 4) THEN (0.6789) ELSE IF(months
= 5) THEN(0.6966) ELSE IF(months = 6) THEN (0.6673) ELSE IF(months = 7) THEN
(0.6478) ELSE IF(months = 8) THEN (0.6428) ELSE IF(months = 9) THEN (0.6673)

ELSE IF(months = 10) THEN (0.6938) ELSE IF(months =11) THEN(0.7016) ELSE
IF(months=12)THEN (0.7018) ELSE 0

DOCUMENT: Green forage dry matter digestibility

Green_forage = 2000 {kg DM}

MPPT_RF = RANDOM (0, 1)

JANRAIN = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.292) then 16 else if
(MPPT_RF<0.625) then 45 else if (MPPT_RF<0.854) then 75 else if
(MPPT_RF<0.958) then 105 else if (MPPT_RF<1) then 135 else 0

FEBRAIN = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.191) then 16 else if
(MPPT_RF<0.595) then 45 else if (MPPT_RF<0.808) then 75 else if
(MPPT_RF<0.957) then 105 else if (MPPT_RF<1) then 135 else 0

MARRAIN = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.021) then 16 else if
(MPPT_RF<0.191) then 45 else if (MPPT_RF<0.489) then 75 else if
(MPPT_RF<0.787) then 105 else if (MPPT_RF<0.915) then 135 else if (MPPT_RF<1)
then 165 else 0

APRIRAIN = if (MPPT_RF<0.01) then 0 else if (MPPT_RF<0.043) then 30 else if
(MPPT_RF<0.298) then 75 else if (MPPT_RF<0.553) then 105 else if (MPPT_RF<0.808)
then 135 else if (MPPT_RF<0.914) then 165 else if (MPPT_RF<0.978) then 195 else if
(MPPT_RF<1) then 225 else 0

MAYRAIN = if (MPPT_RF<0.021) then 0 else if (MPPT_RF<0.212) then 16 else if
(MPPT_RF<0.446) then 45 else if (MPPT_RF<0.68) then 75 else if
(MPPT_RF<0.871) then 105 else if (MPPT_RF<0.977) then 150 else if (MPPT_RF<1)
then 195 else 0

JUNRAIN = if (MPPT_RF<0.065) then 0 else if (MPPT_RF<0.695) then 16 else if
(MPPT_RF<0.847) then 45 else if (MPPT_RF<0.912) then 75 else if (MPPT_RF<1)
then 150 else 0

JULRAIN = if (MPPT_RF<0.087) then 0 else if (MPPT_RF<0.478) then 8 else if
(MPPT_RF<0.674) then 23 else if (MPPT_RF<0.761) then 38 else if
(MPPT_RF<0.848) then 53 else if (MPPT_RF<0.935) then 68 else if (MPPT_RF<1)
then 83 else 0

AUGRAIN = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.196) then 16 else if
 (MPPT_RF<0.5) then 45 else if (MPPT_RF<0.761) then 75 else if (MPPT_RF<0.87)
 then 105 else if (MPPT_RF<0.935) then 135 else if (MPPT_RF<1) then 165 else 0
 SEPTRAIN = if (MPPT_RF<0.01) then 0 else if (MPPT_RF<0.022) then 16 else
 if (MPPT_RF<0.222) then 45 else if (MPPT_RF<0.442) then 75 else
 if (MPPT_RF<0.732) then 105 else if (MPPT_RF<0.91) then 135 else if (MPPT_RF<1)
 then 165 else 0
 OCTRAIN = if (MPPT_RF<0.04) then 0 else if (MPPT_RF<0.065) then 30 else if
 (MPPT_RF<0.195) then 75 else if (MPPT_RF<0.521) then 105 else if
 (MPPT_RF<0.738) then 135 else if (MPPT_RF<0.825) then 165 else if
 (MPPT_RF<0.912) then 195 else if (MPPT_RF<0.977) then 255 else if (MPPT_RF<1)
 then 285 else 0
 NOVRAIN = if (MPPT_RF<0.02) then 0 else if (MPPT_RF<0.043) then 30 else if
 (MPPT_RF<0.239) then 75 else if (MPPT_RF<0.435) then 105 else if
 (MPPT_RF<0.674) then 135 else if (MPPT_RF<0.848) then 165 else if
 (MPPT_RF<0.957) then 195 else if (MPPT_RF<0.979) then 225 else if (MPPT_RF<1)
 then 255 else 0
 DECRRAIN = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.114) then 16 else if
 (MPPT_RF<0.387) then 45 else if (MPPT_RF<0.728) then 75 else if
 (MPPT_RF<0.91) then 105 else if (MPPT_RF<0.955) then 150 else if
 (MPPT_RF<0.978) then 195 else if (MPPT_RF<1) then 225 else 0
 Monthly_rainfall = IF(months=1) THEN(Janrain) ELSE IF(months=2) THEN (Febrain)
 ELSE IF(months=3) THEN (Marrain) ELSE IF(months=4) THEN(Aprirain) ELSE
 IF(months=5) THEN (Mayrain) ELSE IF(months=6) THEN (Junrain) ELSE
 IF(months=7) THEN (Julrain) ELSE IF(months=8) THEN (Augrain) ELSE
 IF(months=9) THEN (Septrain) ELSE IF(months=10) THEN (Octrain) ELSE
 IF(months=11) THEN (Novrain) ELSE IF(months=12) THEN (Decrain) ELSE 0
 Rain_use_effeciency = 4 {kg DM/mm/ha}
 KMs = (111.9)/ (1+106.2*EXP (-0.0022*Monthly rainfall*Rain_use_effeciency))
 HAGRF = (1.1*Green_forage)/ (KMs+Green forage)
 HAGRF1 = IF (HAGRF>1) THEN (1) ELSE (HAGRF)

$$GFCFD = 1.67 \cdot (GFDMD - 0.34)$$

$$GFCP = \text{IF}(\text{months} = 1) \text{ THEN } (0.0375) \text{ ELSE IF } (\text{months} = 2) \text{ THEN } (0.027) \text{ ELSE} \\ \text{IF}(\text{months} = 3) \text{ THEN } (0.0295) \text{ ELSE IF}(\text{months} = 4) \text{ THEN } (0.0375) \text{ ELSE IF}(\text{months} \\ = 5) \text{ THEN } (0.0535) \text{ ELSE IF}(\text{months} = 6) \text{ THEN } (0.0315) \text{ ELSE IF}(\text{months} = 7) \text{ THEN} \\ (0.039) \text{ ELSE IF}(\text{months} = 8) \text{ THEN } (0.04) \text{ ELSE IF}(\text{months} = 9) \text{ THEN } (0.0365) \\ \text{ELSE IF}(\text{months} = 10) \text{ THEN } (0.04) \text{ ELSE IF}(\text{months} = 11) \text{ THEN } (0.0625) \text{ ELSE} \\ \text{IF}(\text{months} = 12) \text{ THEN } (0.044) \text{ ELSE } 0$$

DOCUMENT: Green forage crude protein

$$GFCFP = 3.509 \cdot (GFCP - 0.015)$$

$$GFDESI = GFCFD \cdot GFCFP$$

DOCUMENT: Green forage digestibility index

$$DFCP = 0.039$$

DOCUMENT: Crude protein of dry forage

$$DFCFP = 3.509 \cdot (DFCP - 0.015)$$

$$DFDMD = 0.6478$$

DOCUMENT: Digestibility of dry forage

$$DFCFD = 1.67 \cdot (DFDMD - 0.34)$$

$$DFDESI = DFCFP \cdot DFCFD$$

DOCUMENT: Dry forage digestibility index

$$\text{SUMDESI} = \text{IF } (\text{months} = 4) \text{ OR } (\text{months} = 10) \text{ OR } (\text{months} = 5) \text{ OR } (\text{months} = 11) \\ \text{THEN } (GFDESI) \text{ ELSE } (DFDESI + GFDESI)$$

$$PRGF = GFDESI / \text{SUMDESI}$$

$$PGFD = (\text{HAGRF1} \cdot PRGF)$$

DOCUMENT: Proportional of the green forage in the diet

$$DD = (GFDMD \cdot PGFD) + ((1 - PGFD) \cdot DFDMD)$$

$$TDN = DD \cdot 0.92$$

$$MEd = 3.62 \cdot (TDN) \text{ \{Mcal/day\}}$$

$$NEmd = 1.37 \cdot MEd - 0.138 \cdot MEd^2 + 0.0105 \cdot MEd^3 - 1.12 \text{ \{Mcal/kg\}}$$

$$DM_{\text{yearlings}} = BW_{\text{yearlings}}^{0.75} \cdot (0.1493 \cdot NEmd - 0.046 \cdot NEmd^2 - 0.0196) \cdot 30 \text{ \{kg} \\ \text{DM /month\}}$$

$$DMIDRY = DM_{\text{Lact}} \text{ \{Kg DM/month\}}$$

Total_pregDry_cows = Drypar32+ dry_par21+ Dry_par_22+ Dry_par_31+ dry_par_4+
Dry_par_42 +Dry_par_5+Dry_par_52 {cows}

TDMIDRY = DMIDRY*Total_pregDry_cows {Kg DM/month}

BWDry = GRAPH (months)

(1.00, 379), (2.00, 355), (3.00, 366), (4.00, 371), (5.00, 373), (6.00, 360), (7.00, 344),
(8.00, 357), (9.00, 337), (10.0, 363), (11.0, 392), (12.0, 392)

Document: Body weight of dry cows

DMIdry2 = ((1.97-(0.75*EXP (0.16*(270 - 280))))/100)*BWDry *30.4 {Kg DM/month}

Total_pregdry_cows2 = Drypar32+Dry_par_22+Dry_par_42+Dry_par_52 {cows}

TDMIdry2 = DMIdry2*Total_pregdry_cows2 {kg DM/month}

BWHP7 = 313 {kg}

DMIPregH7 = ((BWHP7^0.75*((0.2435*NEmd)-(0.0466*NEmd^2)-0.1128))/NEmd)
*30.4{Kg DM /month}

TDMIHP7 = PregHeifers7*DMIPregH7 {kg DM/month}

DDMIPregH7 = DMIPregH7/30.4 {kg DM/day}

DMIPregH893 = DDMIPregH7*((1.71-(0.69*EXP ((0.35*8.6) - 9.3))))

TDMIHP893 = pregheifers893*DMIPregH893 {kg DM/month}

DMIPregH78 = (DMIPregH7*(1+ ((7 - 8.6)*0.0025))) {kg DM/month}

TDMIHPreg78 = pregHeifers78* DMIPregH78 {Kg DM/month}

DMILactPregcows = DMILact {Kg DM/ month}

DOCUMENT: Dry matter intake of heifers

Total_preglact_cows =

(preg_par1)+(Preg_par_2)+(preg_par_3)+(Preg_par_4)+(preg_par_5)+(preg_par_6)
{cows}

TDMIactpregcows = DMILactPregcows*Total_preglact_cows {kg DM/month}

Body_W_steers = 100 {kg}

DMIWeaned_males = Body_W_steers^{0.75}*(0.1493*NEmd-0.046*NEmd²-0.0196)*30.4
{KgDM /month}

TDMIS = DMIWeaned_males*Weaned_males {kg DM/month}

BW_weaned_H = 150 {kg}

$DMI_WHeifers = ((BW_Weaned_H^{0.75} * ((0.2435 * NE_{md}) - (0.0466 * NE_{md}^2) - 0.1128)) / NE_{md}) * 30.4 \text{ {kg DM /month}}$
 $TDMI_WHeifers = DMI_WHeifers * Weaned_heifer_calves \text{ {Kg DM/month}}$
 $TotalDMI_Herd_deand =$
 $TDMI_{Lact} + DMI_{yearlings} + TDMI_{DRY} + TDMI_{dry2} + TDMI_{HP7} + TDMI_{HP893} + TDMI_{HPreg}$
 $78 + TDMI_{lactpregcows} + TDMI_{IS} + TDMI_WHeifers \text{ {kg DM/month}}$
 $Area = 150 \text{ {ha}}$
 $Total_herd_DD_per_Ha = TotalDMI_Herd_deand / Area \text{ {kg DM/ha}}$
 $Dry_Forage = 600 \text{ {kg Dm}}$
 $TSC = Dry_Forage + Green_forage \text{ {kg DM}}$
 $RIF = GRAPH (TSC)$
 $(0.00, 0.1), (500, 0.6), (1000, 0.82), (1500, 0.9), (2000, 0.95), (2500, 1.00), (3000, 1.00)$
 $RIF1 = IF (RIF > 1) THEN (1) ELSE (RIF)$
DOCUMENT: proportional of forage grazed depending on the available forage
 $Actual_intake_per_ha = Total_herd_DD_per_Ha * RIF1$
 $Forage_growth = (Monthly_rainfall * Rain_use_effeciency) \text{ {kg DM /ha/month}}$
 $GFC = (Actual_intake_per_ha * PGFD) \text{ {kg DM/month}}$
 $Senescence_rate = 0.195$
 $SEN_in = IF (months = 3) OR (months = 4) OR (months = 9) OR (months = 10) THEN (0)$
 $ELSE ((Green_forage - GFC) * Senescence_rate) \text{ {kg DM/month}}$
 $SEN = 0$
 $Sen_Loss = SEN * 0.2$
 $SEN_out = SEN - Sen_Loss$
DOCUMENT: Senescence forage
 $DFC = Actual_intake_per_ha - GFC \text{ {kg DM/month}}$
 $Monthly_temperature = IF (months = 1) THEN (26.9) ELSE IF (months = 2) THEN (27.7) ELSE IF (months = 3) THEN (27.1) ELSE IF (months = 4) THEN (27.1) ELSE IF (months = 5) THEN (26.1) ELSE IF (months = 6) THEN (26.7) ELSE IF (months = 7) THEN (27.2) ELSE IF (months = 8) THEN (27.4) ELSE IF (months = 9) THEN (27.2)$

ELSE IF(months = 10) THEN (26.2) ELSE IF(months =11) THEN(25.6) ELSE
 IF(months=12)THEN (26.1) ELSE 0
 DOCUMENT: Average monthly temeperature
 $Dead_rate = 1 - \exp(-0.003077 * Monthly_rainfall) + 0.0005 * Monthly_temperature$
 $Dry_Forage_litter = \text{IF} (months=4) \text{ OR } (months=9) \text{ OR } (months=10) \text{ THEN}$
 $(Dry_Forage) \text{ ELSE } (Dead_rate * (Dry_Forage - DFC)) \text{ \{Kg DM /ha/month\}}$
 DOCUMENT: Dry forage that decomposes
 $ANFC = 0 \text{ \{kgDM/month\}}$
 $ANFC_IN = DFC + GFC \text{ \{kgDM/month\}}$
 $ANFC_OUT = \text{IF} (months=1) \text{ THEN } (ANFC) \text{ ELSE } (0) \text{ \{kgDM/year\}}$
 $ANRF = 0 \text{ \{mm\}}$
 $ANRF_IN = Monthly_rainfall \text{ \{mm/month\}}$
 $ANRF_OUT = \text{IF} (months=1) \text{ THEN } (ANRF) \text{ ELSE } (0)$
 $Replacement_heifers = 16 \text{ \{cows\}}$
 $Conception_rate = 0.98$
 $Mortality_of_weaned_females = 0.073/12 \text{ \{cows\}}$
 $dead_female_weaned_calves = \text{LEAKAGE OUTFLOW}$
 $\text{LEAKAGE FRACTION} = (Weaned_heifer_calves * Mortality_of_weaned_females)$
 $\text{\{cow\}}$
 $growing_heifers = \text{CONVEYOR OUTFLOW}$
 $\text{TRANSIT TIME} = \text{Growth_period}$
 $\text{ConcHeifers} = (Replacement_heifers) * Conception_rate \text{ \{cows/month\}}$
 $Jan_cal_Mlk = 0$
 $DDMILact = DMILact/30.4 \text{ \{Kg DM/day\}}$
 $MEcontent = (((DD * 1000) - 61) * 0.011) + 3.2 / 4.184 \text{ \{Mcal/ha\}}$
 $NEcontent = (MEcontent + 0.2473) / 1.8315$
 $NEltotallact = DDMILact * NEcontent * RIF1 \text{ \{Mcal/d\}}$
 $MEact_lact = ((0.006 * DDMILact * ((0.9 - GFDMD) * 0.92)) + (0.05 * 1.5 /$
 $((0.002471 * Green_forage) + 3))) * BWLact / 4.186 \text{ \{Mcal/d\}}$
 DOCUMENT: Meatabolisable energy required for activity and grazing for lactating
 cows

$$\text{NEact_lact} = (1.37 * \text{MEact_lact} - 0.138 * \text{MEact_lact}^2 + 0.0105 * \text{MEact_lact}^3 - 1.12) * 0.5$$

DOCUMENT: conversion of metabolisable energy to net energy

$$\text{NEmaintLactCows} = (0.96 * \text{BWLact}^{0.75}) * 0.080 + (\text{NEact_lact}) \text{ {Mcal/ day}}$$

$$\text{NEBal_lact_cows} = (\text{NEltotallact} - \text{NEmaintLactCows}) \text{ {Mcal/day}}$$

$$\text{SNF} = 8.3$$

$$\text{NE_in_milk} = (0.386 * \text{MILKfat} + 0.205 * \text{SNF} + 0.236) / 4.186 \text{ {Mcal/kg}}$$

$$\text{MEL} = (\text{NE_in_milk} * \text{PMY1})$$

$$\text{MEL1} = \text{IF } (\text{MEL} = 0) \text{ THEN } (1) \text{ ELSE } (\text{MEL})$$

$$\text{MFRAC} = \text{NEBal_lact_cows} / \text{MEL1}$$

$$\text{MFRAC1} = \text{IF } (\text{MFRAC} > 1) \text{ THEN } (1) \text{ ELSE } (\text{MFRAC})$$

$$\text{Yr_day} = \text{MFRAC1} * \text{PMY1}$$

Document: Daily milk yield for cows calving in January (cows calving in the other months of the year used a similar formula)

$$\text{Jan_M_in} = \text{Yr_day}$$

$$\text{JanMin_out} = \text{IF } (\text{MOL} = 9) \text{ THEN } (\text{Jan_cal_Mlk}) \text{ ELSE } (0)$$

$$\text{MOL2} = \text{GRAPH (months)}$$

$$(1.00, 12.0), (2.00, 1.00), (3.00, 2.00), (4.00, 3.00), (5.00, 4.00), (6.00, 5.00), (7.00, 6.00), (8.00, 7.00), (9.00, 8.00), (10.0, 9.00), (11.0, 10.0), (12.0, 11.0)$$

$$\text{MOL_3} = \text{GRAPH (months)}$$

$$(1.00, 11.0), (2.00, 12.0), (3.00, 1.00), (4.00, 2.00), (5.00, 3.00), (6.00, 4.00), (7.00, 5.00), (8.00, 6.00), (9.00, 7.00), (10.0, 8.00), (11.0, 9.00), (12.0, 10.0)$$

$$\text{MOL_4} = \text{GRAPH (months)}$$

$$(1.00, 10.0), (2.00, 11.0), (3.00, 12.0), (4.00, 1.00), (5.00, 2.00), (6.00, 3.00), (7.00, 4.00), (8.00, 5.00), (9.00, 6.00), (10.0, 7.00), (11.0, 8.00), (12.0, 9.00)$$

$$\text{MOL_5} = \text{GRAPH (months)}$$

$$(1.00, 9.00), (2.00, 10.0), (3.00, 11.0), (4.00, 12.0), (5.00, 1.00), (6.00, 2.00), (7.00, 3.00), (8.00, 4.00), (9.00, 5.00), (10.0, 6.00), (11.0, 7.00), (12.0, 8.00)$$

$$\text{MOL_6} = \text{GRAPH (months)}$$

$$(1.00, 8.00), (2.00, 9.00), (3.00, 10.0), (4.00, 11.0), (5.00, 12.0), (6.00, 1.00), (7.00, 2.00), (8.00, 3.00), (9.00, 4.00), (10.0, 5.00), (11.0, 6.00), (12.0, 7.00)$$

$$\text{MOL_7} = \text{GRAPH (months)}$$

(1.00, 7.00), (2.00, 8.00), (3.00, 9.00), (4.00, 10.0), (5.00, 11.0), (6.00, 12.0), (7.00, 1.00), (8.00, 2.00), (9.00, 3.00), (10.0, 4.00), (11.0, 5.00), (12.0, 6.00)

MOL_8 = GRAPH (months)

(1.00, 6.00), (2.00, 7.00), (3.00, 8.00), (4.00, 9.00), (5.00, 10.0), (6.00, 11.0), (7.00, 12.0), (8.00, 1.00), (9.00, 2.00), (10.0, 3.00), (11.0, 4.00), (12.0, 5.00)

MOL_9 = GRAPH (months)

(1.00, 5.00), (2.00, 6.00), (3.00, 7.00), (4.00, 8.00), (5.00, 9.00), (6.00, 10.0), (7.00, 11.0), (8.00, 12.0), (9.00, 1.00), (10.0, 2.00), (11.0, 3.00), (12.0, 4.00)

MOL_10 = GRAPH (months)

(1.00, 4.00), (2.00, 5.00), (3.00, 6.00), (4.00, 7.00), (5.00, 8.00), (6.00, 9.00), (7.00, 10.0), (8.00, 11.0), (9.00, 12.0), (10.0, 1.00), (11.0, 2.00), (12.0, 3.00)

MOL_11 = GRAPH (months)

(1.00, 3.00), (2.00, 4.00), (3.00, 5.00), (4.00, 6.00), (5.00, 7.00), (6.00, 8.00), (7.00, 9.00), (8.00, 10.0), (9.00, 11.0), (10.0, 12.0), (11.0, 1.00), (12.0, 2.00)

MOL_12 = GRAPH (months)

(1.00, 2.00), (2.00, 3.00), (3.00, 4.00), (4.00, 5.00), (5.00, 6.00), (6.00, 7.00), (7.00, 8.00), (8.00, 9.00), (9.00, 10.0), (10.0, 11.0), (11.0, 12.0), (12.0, 1.00)

Feb_cal_mlk = 0

MSmilk2 = IF (MOL2<9) THEN (MOL2) ELSE 0)

PMY2 = MSmilk2/ (IRC*EXP (0.5*MSmilk2))

DOCUMENT: Potential milk yield for cow calving in February (cows calving in the other months of the year used a similar equation.

FCM2 = (0.4*PMY2) + (15*(MILKFat/100)*PMY2) {kg/day}

DMI2 = (0.1*FCM2+0.025*BWLact) {kg DM/month}

DOCUMENT: Dry matter intake for cow calving in February (cows calving in the other months of the year used a similar equation.

NEI_totallact2 = DMI2*NEcontent*RIF1 {Mcal/d}

NEBal_lact_cow_2 = (NEI_totallact2-NEmaintLactCows) {Mcal/day}

MEL2 = (NE_in_milk*PMY2)/0.82

MEL21 = IF (MEL2=0) THEN (1) ELSE (MEL2)

MFRAC2 = NEBal_lact_cow_2/MEL21

MFRACT21 = IF (MFRACT2>1) THEN (1) ELSE (MFRACT2)
 Yrd2 = MFRACT21*PMY2
 Feb_M_in = Yrd2
 Feb_M_out = IF (MOL2 = 9) THEN (Feb_cal_mlk) ELSE (0)
 JANcow = 0 {cows}
 calving_heifers = CONVEYOR OUTFLOW
 TRANSIT TIME = gestationheifer893 {months}
 Cal_par_1 = CONVEYOR OUTFLOW
 Cal_par_2 = CONVEYOR OUTFLOW
 cal_par_3 = CONVEYOR OUTFLOW
 cal_par_4 = CONVEYOR OUTFLOW
 cal_par_5 = CONVEYOR OUTFLOW
 CALV = INT
 (calving_heifers+Cal_par_1+Cal_par_2+Cal_par_3+cal_par_4+cal_par_5) {cows}
 DOCUMENT: Calves born per month
 lJan = INT (IF (months=1) THEN (CALV) ELSE (0))
 OJan = IF (months=9) THEN (JANcow) ELSE (0)
 Yearling_steers = 4 {cows}
 mortality_weaned_males = 0.059/12 {cows}
 MCdeaths = LEAKAGE OUTFLOW
 LEAKAGE FRACTION = Weaned_males*mortality_weaned_males {cow/moonth}
 Growing_steers = CONVEYOR OUTFLOW
 TRANSIT TIME = growth_period_2
 Steers_sold = Yearling_steers
 Dead_par_6 = LEAKAGE OUTFLOW
 LEAKAGE FRACTION = Par_6_cows*Cow_mortality_rate {cows}
 Conc_par_6 = CONVEYOR OUTFLOW
 TRANSIT TIME = months_open
 Culled_cows = IF (months=5) or (months=11) THEN (preg_par_6) ELSE (0)
 DOCUMENT: Culled cows were sold of in the month of May and November
 ANFP = 100 {kg DM/ha/month}

ANFP_IN = Forage_growth {KgDM/ha/month}
 ANFP_OUT = IF (months=1) THEN (ANFP) ELSE (0) {Kg Dm/year}
 FEB = INT (IF (months=2) THEN (CALV) ELSE (0))
 DOCUMENT: Cows calving in February
 OFEB = IF (months=10) THEN (FEBCOW) ELSE (0)
 IMAR = INT (IF (months=3) THEN (CALV) ELSE (0))
 OMAR = IF (months=11) THEN (MARCOW) ELSE (0)
 APRCOW = 0 {cows}
 IAPR = INT (I F (months=4) THEN (CALV) ELSE (0))
 OAPR = IF (months=12) THEN (APRCOW) ELSE (0)
 MAYCOW = 0 {cows}
 IMAY = INT (IF (months=5) THEN (CALV) ELSE (0))
 OMay = IF (months=1) THEN (MAYCOW) ELSE (0)
 JUNCOW = 0 {cows}
 IJUN = INT (IF (months=6) THEN (CALV) ELSE (0))
 OJUN = IF (months=2) THEN (JUNCOW) ELSE (0)
 JULCOW = 0 {cows}
 IJUL = INT (IF (months=7) THEN (CALV) ELSE (0))
 OJUL = IF (months=3) THEN (JULCOW) ELSE (0)
 AUGCOW = 0 {cows}
 IAUG = INT (IF (months=8) THEN (CALV) ELSE (0))
 OAUG = IF (months= 4) THEN (AUGCOW) ELSE (0)
 SEPCOW = 0 {cows}
 ISEP = INT (IF (months=9) THEN (CALV) ELSE (0))
 OSEPT = IF (months=5) THEN (SEPCOW) ELSE (0)
 OCTCOW = 0 {cows}
 IOCT = INT (IF (months=10) THEN (CALV) ELSE (0))
 OOct = IF (months=6) THEN (OCTCOW) ELSE (0)
 Mar_cal_Mlk = 0
 NOVCOW = 0 {cows}
 INOV = INT (IF (months=11) THEN (CALV) ELSE (0))

ONOV = IF (months=7) THEN (NOVCOW) ELSE (0)
 DECCOW = 0 {cows}
 IDEC = INT (IF (months=12) THEN (CALV) ELSE (0))
 ODEC = IF (months=8) THEN (DECCOW) ELSE (0)
 Dec_M_out = IF (MOL_12 = 9) THEN (Dec_cal_MLk) ELSE (0)
 TLU = (PregHeifers7*0.6)+ (pregHeifers78*0.6)+ (Weaned_heifer_calves*0.6)+
 (Weaned_males*0.6)+ (Yearling_steers*0.6)+ (Total_pregDry_cows*1.2)+
 (Total_pregdry_cows2*1.2)+ (Total_preglact_cows*1.2)+ (Totlact_nonpreg*1.2)+
 (Female_calves*0.25)+ (male_calves*0.25)+(Replacement_heifers*0.6)
 DOCUMENT:Total Tropical Livestock Unit
 Cow_income = culled_cows*Price_of_cows
 APR_Yr_day = APRCOW*Yrd4 {kg/day}
 DOCUMENT: Total milk yield per produced by cows that calved in April (cows that
 calved in the other months of the year used a similar equation.
 Monthly_Herd_milk_yield = HerdTestday_mily_yield*30.4
 Milk_price = If (months = 12) OR (months=1) OR (months=2) OR (months=6) OR
 (months=7) OR (months = 8) THEN (300) ELSE (180)
 Milk_income = Monthly_Herd_milk_yield*Milk_price
 Steer_pricce = 200000
 Steer_income = Steers_sold*Steer_pricce
 INcome = Cow_income+Milk_income +Steer_income
 Var_cost = Drug_cost+labour_cost+Drench+Acariside_cost+MInearal_lick_cost
 DOCUMENT: Total variable cost
 Annual_income = 0
 Month_income = INcome-Var_cost
 Ann_Income_IN = Month_income
 Ann_Income_OUT = IF (months=1) THEN (Annual_income) ELSE (0)
 DOCUMENT: income emptied at the end of the year
 Ann_Milk = 0
 AN_MLK_In = Monthly_Herd_milk_yield
 AN_MLK_Out = IF (months= 1) THEN (Ann_Milk) ELSE (0)

DOCUMENT: Milk yield emptied at the end of the year

Female_cal_Mort_rate = 0.083/12 {cows}

Female_calves_deaths = LEAKAGE OUTFLOW

LEAKAGE FRACTION = (Female_calves*Female_cal_Mort_rate) {cow/month}

Weaning_Female_calves = CONVEYOR OUTFLOW

TRANSIT TIME = Weaning_age

pregn6 = CONVEYOR OUTFLOW

TRANSIT TIME = gestationh7 {months}

FML_Nursing_calve = CALV*0.5 {cows/month}

Macal_Mort_rate = 0.059/12 {cows/month}

Male_calves_deaths = LEAKAGE OUTFLOW

LEAKAGE FRACTION = male_calves*Macal_Mort_rate

Weaning_male_calves = CONVEYOR OUTFLOW

TRANSIT TIME = Weaning_age

Male_Nursing_calve = CALV*0.5 {cows/month}

Mort_rate = 0.065/12{cows}

Dead_par_1 = LEAKAGE OUTFLOW

LEAKAGE FRACTION = Par_1*Mort_rate {cows}

DOCUMENT: Parity 1 dead cows (cows in other parities used a similar equation)

Conc_par_1 = CONVEYOR OUTFLOW

TRANSIT TIME = months_open

DOCUMENT: Conceiving cows in parity 1 (Conceiving cows in other parities used a similar equation)

IFEB_M = IF (months=2) THEN (CALV*0.5) ELSE (0)

IJAN_M = IF (months=1) THEN (CALV*0.5) ELSE (0)

IMAR_M = IF (months=3) THEN (CALV*0.5) ELSE (0)

IAPR_M = INT (IF (months=4) THEN (CALV*0.5) ELSE (0))

IMAY_M = INT (IF (months=5) THEN (CALV*0.5) ELSE (0))

IJUN_M = INT (IF (months=6) THEN (CALV*0.5) ELSE (0))

IJUL_M = INT (IF (months=7) THEN (CALV*0.5) ELSE (0))

IAUG_M = INT (IF (months=8) THEN (CALV*0.5) ELSE (0))

ISEP_M = INT (IF (months=9) THEN (CALV*0.5) ELSE (0))
 IOCT_M = INT (IF (months=10) THEN (CALV*0.5) ELSE (0))
 INOV__M = INT (IF (months=11) THEN (CALV*0.5) ELSE (0))
 IDEC_M = INT (IF (months=12) THEN (CALV*0.5) ELSE (0))
 SR = Area/TLU
 DDMIDRY = DMIDRY/30.4
 DOG = 235
 MW = 400{kg}
 CBW = 0.06275*MW {kg}
 CW = 18+ ((DOG - 280)*0.665)*CBW/45 {kg}
 DNED = 0.086*((0.96*BWDry)-CW)^{0.75}
 Wheifers = 80
 SRControl = 1.3 {ha/TLU}
 Total_Preg_heifers =
 PregHeifers7+pregHeifers78+pregheifers893+Weaned_heifer_calves {cows}
 DDMIPregH78 = DMIPregH78/30.4 {kg DM/day}
 DDMI_WHeifers = DMI_WHeifers/30.4 {kg DM/day}
 DDMIWeaned_males = DMIWeaned_males/30.4 {kg DM/day}
 SBWWeaned_males = 0.96*Body_W_steers {kG}
 DNEmaintWeaned_males = 0.086*(SBWWeaned_males)^{0.75} {Mcal/day}
 growth_time = time
 NEItotal_H = DMI_WHeifers*NEcontent *RIF1 {Mcal/month}
 SBWH = 0.96*BW_Weaned_H {Kg}
 MEActH = ((0.006*DDMI_WHeifers*((0.9-GFDMD)*0.92)) + (0.05*1.5/
 ((0.002471*Green_forage)+3)))*BW_Weaned_H/4.186 {Mcal/d}
 NEActH = (1.37*MEActH-0.138*MEActH²+0.0105*MEActH³-1.12)*0.5
 NEmaintH = (0.086*(SBWH)^{0.75} + NEActH)*30.4 {Mcal/ month}
 NEBalance_heifer = NEItotal_H-NEmaintH {Mcal/day}
 NE_Hgrowth = NEBalance_heifer
 Adult_weight_cow = 400 {kg}
 Weight_EBW_H = (0.91*Wheifers*550)/Adult_weight_cow {kg}

$GR1 = NE_Hgrowth / (27.14 * 0.2788 / Weight_EBW_H^{0.1107} + 45.20 * 0.0039388 * Weight_EBW_H^{0.788})$
 $Gr = 0$
 $Growth_rate_H = IF (growth_time < 18) THEN GR1 ELSE (Gr)$
 $Dead_par_5 = CONVEYOR_OUTFLOW$
 $TRANSIT_TIME = Par_5_cows * Cow_mortality_rate \{cows\}$
 $growth_time_1 = time$
 $NEItotal_ST = NEcontent * DMIWeaned_males * RIF1 \{Mcal/month\}$
 $MEactWeaned_males = ((0.006 * DDMIWeaned_males * ((0.9 - GFDMD) * 0.90)) + (0.05 * 1.5 / ((0.02471 * Green_forage) + 3))) * SBWWeaned_males / 4.186 \{Mcal/d\}$
 $NEactWeaned_males = (1.37 * MEactWeaned_males - 0.138 * MEactWeaned_males^2 + 0.0105 * MEactWeaned_males^3 - 1.12) * 0.5$
 $NEactWEM = IF (NEactWeaned_males < 0) THEN (0) ELSE (NEactWeaned_males)$
 $NEmaitWeaned_males = (DNEmaintWeaned_males + NEactWEM) * 30.4 \{Mcal/month\}$
 $NEBalance_Steer = NEItotal_ST - NEmaitWeaned_males \{Mcal/month\}$
 $NE_STgrowth = NEBalance_Steer \{Mcal/month\}$
 $Adult_weight_bull = 460 \{kg\}$
 $Weight_EBW = (0.91 * Body_W_steers * 550) / Adult_weight_bull \{kg\}$
 $Growth_rate = IF (growth_time_1 < 18) THEN (NE_STgrowth / (20.06 * 0.2788 / Weight_EBW^{0.1107} + 33.41 * 0.0039388 * Weight_EBW^{0.788})) ELSE (0) \{kg/month\}$
 $BWPreg = BWLact$
 $NEactlactpreg = ((0.006 * DDMILact * (0.9 * GFDMD * 0.92)) + (0.05 * 1.5 / ((0.002471 * Green_forage) + 3))) * BWPreg / 4.186 \{Mcal/d\}$
 $MEactHP = ((0.006 * DDMIPregH78 * ((0.9 - GFDMD) * 0.92)) + (0.05 * 1.5 / ((0.002471 * Green_forage) + 3))) * BWHP7 / 4.186 \{Mcal/d\}$
 $NEactHP = (1.37 * MEactHP - 0.138 * MEactHP^2 + 0.0105 * MEactHP^3 - 1.12) * 0.5$
 $NEPreg = (((0.00318 * DOG - 0.0352) * (CBW / 45)) / 0.218) * 30.4 \{Mcal/month\}$
 $MEactDRY = (((0.006 * DDMIDRY * ((0.9 - GFDMD) * 0.92)) + (0.05 * 1.5 / ((0.002471 * Green_forage) + 3))) * BWDry / 4.186) * 0.5 \{Mcal/d\}$

$NEact_dry = (1.37 * MEactDRy - 0.138 * MEactDRy^2 + 0.0105 * MEactDRy^3 - 1.12) * 0.5$
 $NEmaitDry = (DNED + NEact_dry) * 30 \text{ {Mcal/month}}$
 $TotalRNE_Dry = NEmaitDry + NEpreg \text{ {Mcal/month}}$
 $SBWHP = 0.96 * BWHP7 \text{ {Kg}}$
 $NEManithHPreg = (0.086 * (SBWHP - CW)^{0.75} + NEactHP) * 30.4 \text{ {Mcal/ month}}$
 $TotalNERheiferPreg = NEManithHPreg + NEpreg \text{ {Mcal/ month}}$
 $NEmaintPreg_Cows = (((0.096 * BWpreg)^{0.75}) * 0.08 + NEactlactpreg) * 30.4$
 $\text{{Mcal/month}}$
 $Sell_rate_heifer = IF (SR < SRControl) THEN ((SRControl - SR) / SRControl) ELSE (0)$
 $TDMlyearlings = Yearling_steers * DMlyearlings$
 $NEltotallactpreg = NEcontent * DMlactpregcows * RIF1 \text{ {Mcal/d}}$
 $NEBalanceLactPreg = NEltotallactpreg - NEmaintPreg_Cows$
 $NEltotalDry = DMIDRY * NEcontent * RIF1 \text{ {Mcal/month}}$
 $NEBalanceDry = (NEltotalDry - (NEmaitDry + NEpreg)) \text{ {Mcal/month}}$
 $NEltotalHP = DMIPregH78 * NEcontent * 30.4 * RIF1 \text{ {Mcal/d}}$
 $NEBalanceHP = (NEltotalHP - (NEManithHPreg + NEpreg)) \text{ {Mcal7d}}$
 $Janlact_yld = JanMin_out * 30.4$

DOCUMENT: lactation milk yield for cow calving in January. (The same formula was applied to the cows that calve in the other months of the year)

 $GRmargin = 0 \text{ {sh}}$

DOCUMENT: Initial gross margin

 $AF = Dry_Forage + Green_forage + ANFC_IN + SEN$
 $Heifer_price = 634600$
 $Green_forage(t) = Green_forage(t - dt) + (Forage_growth - GFC - SEN_in) * dt$

DOCUMENT: Green forage

 $preg_par_6(t) = preg_par_6(t - dt) + (Conc_par_6 - culled_cows) * dt$
 $Body_W_steers(t) = Body_W_steers(t - dt) + (Growth_rate) * dt$

DOCUMENT: Steer body weight

 $Dry_Forage(t) = Dry_Forage(t - dt) + (SEN_out - DFC - Dry_Forage_litter) * dt$

DOCUMENT: Dry forage

 $SEN(t) = SEN(t - dt) + (SEN_in - SEN_out - Sen_Loss) * dt$

DOCUMENT: Senescencing forage

$$ANFC(t) = ANFC(t - dt) + (ANFC_IN - ANFC_OUT) * dt$$

DOCUMENT: Annual forage consument

$$ANRF(t) = ANRF(t - dt) + (ANRF_IN - ANRF_OUT) * dt$$

DOCUMENT: Annual rainfall

$$\text{Replacement_heifers}(t) = \text{Replacementheifers}(t - dt) + (\text{growing_heifers} - \text{ConcHeifers}) * dt$$

DOCUMENT: Repalcement heifers

$$\text{Jan_cal_Mlk}(t) = \text{Jan_cal_Mlk}(t - dt) + (\text{Jan_M_in} - \text{JanMin_out}) * dt$$

$$\text{Feb_cal_mlk}(t) = \text{Feb_cal_mlk}(t - dt) + (\text{Feb_M_in} - \text{Feb_M_out}) * dt$$

$$\text{Mar_cal_Mlk}(t) = \text{Mar_cal_Mlk}(t - dt) + (\text{Mar_M_in} - \text{Mar_m_out}) * dt$$

$$\text{APR_cal_milk}(t) = \text{APR_cal_milk}(t - dt) + (\text{Apr_M_in} - \text{Apr_M_out}) * dt$$

$$\text{May_cal_mlk}(t) = \text{May_cal_mlk}(t - dt) + (\text{May_M_in} - \text{May_m_out}) * dt$$

$$\text{June_cal_mlk}(t) = \text{June_cal_mlk}(t - dt) + (\text{June_M_in} - \text{June_M_out}) * dt$$

$$\text{Jul_cal_mik}(t) = \text{Jul_cal_mik}(t - dt) + (\text{JUL_M_in} - \text{JUL_M_out}) * dt$$

$$\text{Aug_cal_MLk}(t) = \text{Aug_cal_MLk}(t - dt) + (\text{Aug_M_In} - \text{Aug_M_out}) * dt$$

$$\text{Sept_cal_milk}(t) = \text{Sept_cal_milk}(t - dt) + (\text{Sept_m_in} - \text{Sept_out}) * dt$$

$$\text{Oct_cal_MLk}(t) = \text{Oct_cal_MLk}(t - dt) + (\text{Oct_M_In} - \text{Oct_M_out}) * dt$$

$$\text{Nov_cal_MLK}(t) = \text{Nov_cal_MLK}(t - dt) + (\text{Nov_M_in} - \text{Nov_M_out}) * dt$$

$$\text{Dec_cal_MLk}(t) = \text{Dec_cal_MLk}(t - dt) + (\text{Dec_M_in} - \text{Dec_M_out}) * dt$$

DOCUMENT: Milk yiled by cows that calve in the respective months

$$\text{Yearling_steers}(t) = \text{Yearling_steers}(t - dt) + (\text{Growing_steers} - \text{Steers_sold}) * dt$$

$$ANFP(t) = ANFP(t - dt) + (ANFP_IN - ANFP_OUT) * dt$$

DOCUMENT: Annual forage produnced

$$\text{JANcow}(t) = \text{JANcow}(t - dt) + (\text{IJan} - \text{OJan}) * dt$$

$$\text{FEBCOW}(t) = \text{FEBCOW}(t - dt) + (\text{IFEB} - \text{OFEB}) * dt$$

$$\text{MARCOW}(t) = \text{MARCOW}(t - dt) + (\text{IMAR} - \text{OMAR}) * dt$$

$$\text{APRCOW}(t) = \text{APRCOW}(t - dt) + (\text{IAPR} - \text{OAPR}) * dt$$

$$\text{MAYCOW}(t) = \text{MAYCOW}(t - dt) + (\text{IMAY} - \text{OMAY}) * dt$$

$$\text{JUNCOW}(t) = \text{JUNCOW}(t - dt) + (\text{IJUN} - \text{OJUN}) * dt$$

$$\text{JULCOW}(t) = \text{JULCOW}(t - dt) + (\text{IJUL} - \text{OJUL}) * dt$$

$AUGCOW(t) = AUGCOW(t - dt) + (IAUG - OAUG) * dt$
 $SEPCOW(t) = SEPCOW(t - dt) + (ISEP - OSEPT) * dt$
 $OCTCOW(t) = OCTCOW(t - dt) + (IOCT - OOCT) * dt$
 $NOVCOW(t) = NOVCOW(t - dt) + (INOV - ONOV) * dt$
 $DECCOW(t) = DECCOW(t - dt) + (IDEC - ODEC) * dt$
DOCUMENT: Tracking the number of cows that calve in the respective months
 $Annual_income(t) = Annual_income(t - dt) + (Ann_Income_IN - Ann_Income_OUT) * dt$
 $Ann_Milk(t) = Ann_Milk(t - dt) + (AN_MLK_In - AN_MLK_Out) * dt$
 $Wheifers(t) = Wheifers(t - dt) + (Growth_rate_H) * dt$
 $GRmargin(t) = GRmargin(t - dt) + (INcome - Var_cost) * dt$
 $Par_5_cows(t) = Par_5_cows(t - dt) + (cal_par_4 - Dead_par_5 - Conc_par_5) * dt$
 $PregHeifers7(t) = PregHeifers7(t - dt) + (ConcHeifers - pregh6) * dt$
 $Par_1(t) = Par_1(t - dt) + (calving_heifers - Conc_par_1 - Dead_par_1) * dt$
 $Weaned_heifer_calves(t) = Weaned_heifer_calves(t - dt) +$
 $(Weaning_Female_calves - growing_heifers - dead_female_weaned_calves) * dt$
 $pregHeifers78(t) = pregHeifers78(t - dt) + (pregh6 - pregh893) * dt$
 $Female_calves(t) = Female_calves(t - dt) + (FML_Nursing_calve -$
 $Weaning_Female_calves - Female_calves_deaths) * dt$
 $Weaned_males(t) = Weaned_males(t - dt) + (Weaning_male_calves -$
 $Growing_steers - MCdeaths) * dt$
 $male_calves(t) = male_calves(t - dt) + (Male_Nursing_calve - Weaning_male_calves$
 $- Male_calves_deaths) * dt$
 $Par_2_cows(t) = Par_2_cows(t - dt) + (Cal_par_1 - Conc_par_2 - dead_par_2) * dt$
 $preg_par1(t) = preg_par1(t - dt) + (Conc_par_1 - drying_par1) * dt$
 $Dry_par12(t) = Dry_par12(t - dt) + (drying_par_12 - Cal_par_1) * dt$
 $Dry_par11(t) = Dry_par11(t - dt) + (drying_par1 - drying_par_12) * dt$
 $Preg_par_2(t) = Preg_par_2(t - dt) + (Conc_par_2 - drying_par_2) * dt$
 $Dry_par_22(t) = Dry_par_22(t - dt) + (drying_par22 - Cal_par_2) * dt$
 $dry_par21(t) = dry_par21(t - dt) + (drying_par_2 - drying_par22) * dt$
 $Par_3_cows(t) = Par_3_cows(t - dt) + (Cal_par_2 - Conc_par_3 - Dead_par_3) * dt$

$\text{preg_par_3}(t) = \text{preg_par_3}(t - dt) + (\text{Conc_par_3} - \text{drying_par_3}) * dt$
 $\text{Dry_par_31}(t) = \text{Dry_par_31}(t - dt) + (\text{drying_par_3} - \text{drying_par32}) * dt$
 $\text{Par_4_cows}(t) = \text{Par_4_cows}(t - dt) + (\text{cal_par_3} - \text{Conc_par_4} - \text{Dead_par_4}) * dt$
 $\text{Drypar32}(t) = \text{Drypar32}(t - dt) + (\text{drying_par32} - \text{cal_par_3}) * dt$
 $\text{Preg_par_4}(t) = \text{Preg_par_4}(t - dt) + (\text{Conc_par_4} - \text{drying_par_4}) * dt$
 $\text{Dry_par_42}(t) = \text{Dry_par_42}(t - dt) + (\text{drying_par_42} - \text{cal_par_4}) * dt$
 $\text{dry_par_4}(t) = \text{dry_par_4}(t - dt) + (\text{drying_par_4} - \text{drying_par_42}) * dt$
 $\text{preg_par_5}(t) = \text{preg_par_5}(t - dt) + (\text{Conc_par_5} - \text{drying_par_5}) * dt$
 $\text{Dry_par_52}(t) = \text{Dry_par_52}(t - dt) + (\text{drying_par52} - \text{cal_par_5}) * dt$
 $\text{Dry_par_5}(t) = \text{Dry_par_5}(t - dt) + (\text{drying_par_5} - \text{drying_par52}) * dt$
 $\text{Par_6_cows}(t) = \text{Par_6_cows}(t - dt) + (\text{cal_par_5} - \text{Conc_par_6} - \text{Dead_par_6}) * dt$
 $\text{pregheifers893}(t) = \text{pregheifers893}(t - dt) + (\text{pregh893} - \text{calving_heifers}) * dt$
 $\text{FEBM}(t) = \text{FEBM}(t - dt) + (\text{IFEB_M} - \text{OFEB_M}) * dt$
 $\text{JANM}(t) = \text{JANM}(t - dt) + (\text{IJAN_M} - \text{OJan_M}) * dt$
 $\text{MAR_M}(t) = \text{MAR_M}(t - dt) + (\text{IMAR_M} - \text{OMAR_M}) * dt$
 $\text{APRCOW_2}(t) = \text{APRCOW_2}(t - dt) + (\text{IAPR_M} - \text{OAPR_M}) * dt$
 $\text{MAYM}(t) = \text{MAYM}(t - dt) + (\text{IMAY_M} - \text{OMAY_M}) * dt$
 $\text{JUN_M}(t) = \text{JUN_M}(t - dt) + (\text{IJUN_M} - \text{OJUN_M}) * dt$
 $\text{I JUL_M}(t) = \text{JUL_M}(t - dt) + (\text{IJUL_M} - \text{OJUL_M}) * dt$
 $\text{I AUG_M}(t) = \text{AUG_M}(t - dt) + (\text{IAUG_M} - \text{OAUG_M}) * dt$
 $\text{I SEP_M}(t) = \text{SEP_M}(t - dt) + (\text{ISEP_M} - \text{OSEPT_M}) * dt$
 $\text{I OCT_M}(t) = \text{OCT_M}(t - dt) + (\text{IOCT_M} - \text{OOCT_M}) * dt$
 $\text{I NOV_M}(t) = \text{NOV_M}(t - dt) + (\text{INOV_M} - \text{ONOV_M}) * dt$
 $\text{I DECM}(t) = \text{DECM}(t - dt) + (\text{IDEC_M} - \text{ODEC_M}) * dt$
 $\text{Months_open} = \text{RANDOM}(\text{Min_open_months}, \text{max_open_months})\{\text{months}\}$
DOCUMENT: length of open period
 $\text{Months} = \text{COUNTER}(1, 13)$
DOCUMENT: Month of the year (1= January ...12= December)
 $\text{Totlact_nonpreg} = (\text{Par_1}) + (\text{Par_2_cows}) + (\text{Par_3_cows}) + (\text{Par_4_cows}) +$
 $(\text{Par_5_cows}) + (\text{Par_6_cows}) \{\text{cows}\}$
 $\text{TDMILact} = \text{DMILact} * \text{Totlact_nonpreg} \{\text{kg DM/month}\}$

GFDMD = IF(months =1) THEN (0.6874) ELSE IF (months = 2) THEN (0.6698) ELSE
 IF(months =3) THEN (0.6584) ELSE IF(months = 4) THEN (0.6789) ELSE IF(months
 = 5) THEN(0.6966) ELSE IF(months = 6) THEN (0.6673) ELSE IF(months = 7) THEN
 (0.6478) ELSE IF(months = 8) THEN (0.6428) ELSE IF(months = 9) THEN (0.6673)
 ELSE IF(months = 10) THEN (0.6938) ELSE IF(months =11) THEN(0.7016) ELSE
 IF(months=12)THEN (0.7018) ELSE 0

DOCUMENT: Green forage Digestibility

MPPT_RF = RANDOM (0, 1)

Janrain = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.292) then 16 else if
 (MPPT_RF<0.625) then 45 else if (MPPT_RF<0.854) then 75 else if
 (MPPT_RF<0.958) then 105 else if (MPPT_RF<1) then 135 else 0

Febrain = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.191) then 16 else if
 (MPPT_RF<0.595) then 45 else if (MPPT_RF<0.808) then 75 else if
 (MPPT_RF<0.957) then 105 else if (MPPT_RF<1) then 135 else 0

Marrain = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.021) then 16 else if
 (MPPT_RF<0.191) then 45 else if (MPPT_RF<0.489) then 75 else if
 (MPPT_RF<0.787) then 105 else if (MPPT_RF<0.915) then 135 else if (MPPT_RF<1)
 then 165 else 0

Aprirain = if (MPPT_RF<0.01) then 0 else if (MPPT_RF<0.043) then 30 else if
 (MPPT_RF<0.298) then 75 else if (MPPT_RF<0.553) then 105 else if
 (MPPT_RF<0.808) then 135 else if (MPPTRF<0.914) then 165 else if
 (MPPTRF<0.978) then 195 else if (MPPTRF<1) then 225 else 0

Mayrain = if (MPPT_RF<0.021) then 0 else if (MPPT_RF<0.212) then 16 else if
 (MPPT_RF<0.446) then 45 else if (MPPT_RF<0.68) then 75 else if
 (MPPT_RF<0.871) then 105 else if (MPPT_RF<0.977) then 150 else if (MPPT_RF<1)
 then 195 else 0

Junrain = if (MPPT_RF<0.065) then 0 else if (MPPT_RF<0.695) then 16 else if
 (MPPT_RF<0.847) then 45 else if (MPPTRF<0.912) then 75 else if (MPPTRF<1) then
 150 else 0

Julrain = if (MPPT_RF<0.087) then 0 else if (MPPT_RF<0.478) then 8 else if
 (MPPT_RF<0.674) then 23 else if (MPPT_RF<0.761) then 38 else if

(MPPT_RF<0.848) then 53 else if (MPPT_RF<0.935) then 68 else if (MPPT_RF<1)
 then 83 else 0
 Augrain = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.196) then 16 else if
 (MPPT_RF<0.5) then 45 else if (MPPT_RF<0.761) then 75 else if (MPPT_RF<0.87)
 then 105 else if (MPPT_RF<0.935) then 135 else if (MPPT_RF<1) then 165 else 0
 Septrain = if (MPPT_RF<0.01) then 0 else if(MPPT_RF<0.022) then 16 else
 if(MPPT_RF<0.222) then 45 else if(MPPT_RF<0.442) then 75 else
 if(MPPT_RF<0.732) then 105 else if(MPPT_RF<0.91) then 135 else if(MPPT_RF<1)
 then 165 else 0
 Octrain = if (MPPT_RF<0.04) then 0 else if (MPPT_RF<0.065) then 30 else if
 (MPPT_RF<0.195) then 75 else if (MPPT_RF<0.521) then 105 else if
 (MPPT_RF<0.738) then 135 else if (MPPT_RF<0.825) then 165 else if
 (MPPT_RF<0.912) then 195 else if (MPPT_RF<0.977) then 255 else if (MPPT_RF<1)
 then 285 else 0
 Novrain = if (MPPT_RF<0.02) then 0 else if (MPPT_RF<0.043) then 30 else if
 (MPPT_RF<0.239) then 75 else if (MPPT_RF<0.435) then 105 else if
 (MPPT_RF<0.674) then 135 else if (MPPT_RF<0.848) then 165 else if
 (MPPT_RF<0.957) then 195 else if (MPPT_RF<0.979) then 225 else if (MPPT_RF<1)
 then 255 else 0
 Decrain = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.114) then 16 else if
 (MPPT_RF<0.387) then 45 else if (MPPT_RF<0.728) then 75 else if
 (MPPT_RF<0.91) then 105 else if (MPPT_RF<0.955) then 150 else if(MPPT_RF<0.978)
 then 195 else if (MPPT_RF<1) then 225 else 0
 Monthly_rainfall = IF(months=1) THEN(Janrain) ELSE IF(months=2) THEN (Febrain)
 ELSE IF(months=3) THEN (Marrain) ELSE IF(months=4)THEN(Aprirain) ELSE
 IF(months=5) THEN (Mayrain) ELSE IF(months=6) THEN (Junrain) ELSE
 IF(months=7) THEN (Julrain) ELSE IF(months=8) THEN (Augrain) ELSE
 IF(months=9) THEN (Septrain) ELSE IF(months=10) THEN (Octrain) ELSE
 IF(months=11) THEN (Novrain) ELSE IF(months=12) THEN (Decrain) ELSE 0
 KMs = (111.9)/ (1+106.2*EXP (-0.0022*Monthly_rainfall*Rain_use_effeciency))
 HAGRF = (1.1*Green_forage)/ (KMs+Green_forage)

HAGRF1 = IF (HAGRF>1) THEN (1) ELSE (HAGRF)

DOCUMENT: Green forage harvestability coefficient

GFCFD = 1.67*(GFDMD-0.34)

GFCP = IF(months =1) THEN (0.0375) ELSE IF (months = 2) THEN (0.027) ELSE
IF(months =3) THEN (0.0295) ELSE IF(months = 4) THEN (0.0375) ELSE IF(months
= 5) THEN(0.0535) ELSE IF(months = 6) THEN (0.0315) ELSE IF(months = 7) THEN
(0.039) ELSE IF(months = 8) THEN (0.04) ELSE IF(months = 9) THEN (0.0365)
ELSE IF(months = 10) THEN (0.04) ELSE IF(months =11) THEN(0.0625) ELSE
IF(months=12)THEN (0.044) ELSE 0

DOCUMENT: Green forage monthly crude protein

GFCFP = 3.509*(GFCP-0.015)

GFDESI = GFCFD*GFCFP

DFCFP = 3.509*(DFCP-0.015)

DFCFD = 1.67*(DFDMD-0.34)

DFDESI = DFCFP*DFCFD

SUMDESI = IF (months = 4) OR (months=10) OR (months = 5) OR (months = 11)
THEN (GFDESI) ELSE (DFDESI+ GFDESI)

PRGF = GFDESI/SUMDESI

DOCUMENT: Proportional of green forage in the diet

PGFD = (HAGRF1*PRGF)

DD = (GFDMD*PGFD) + ((1-PGFD)*DFDMD)

TDN = DD*0.92

MEd = 3.62*(TDN) {Mcal/day}

NEmd = 1.37*MEd-0.138*MEd²+0.0105*MEd³-1.12 {Mcal/kg}

DM|yearlings = BW_yearlings^{0.75}*(0.1493*NEmd-0.046*NEmd²-0.0196)*30 {kg DM
/month}

DMIDRY = DMILact {Kg DM/month}

Total_pregDry_cows =

Drypar32+dry_par21+Dry_par_22+Dry_par_31+dry_par_4+Dry_par_42+Dry_par_5+
Dry_par_52 {cows}

TDMIDRY = DMIDRY*Total_pregDry_cows {Kg DM/month}

BWDry = GRAPH (months)

(1.00, 379), (2.00, 355), (3.00, 366), (4.00, 371), (5.00, 373), (6.00, 360), (7.00, 344),
(8.00, 357), (9.00, 337), (10.0, 363), (11.0, 392), (12.0, 392)

DOCUMENT: Body weight of dry cows

DMIdry2 = $((1.97 - (0.75 * \text{EXP}(0.16 * (270 - 280)))) / 100) * \text{BWDry} * 30.4$ {Kg DM/month}

Document: Dry matter intake of dry cows

Total_pregdry_cows2 = Drypar32+Dry_par_22+Dry_par_42+Dry_par_52 {cows}

TDMIdry2 = DMIdry2*Total_pregdry_cows2 {kg DM/month}

DMIPregH7 = $((\text{BWHP7}^{0.75} * ((0.2435 * \text{NEmd}) - (0.0466 * \text{NEmd}^2) - 0.1128)) / \text{NEmd})$
*30.4 {Kg DM /month}

TDMIHP7 = PregHeifers7*DMIPregH7 {kg DM/month}

DDMIPregH7 = DMIPregH7/30.4 {kg DM/day}

DMIPregH893 = DDMIPregH7*((1.71-(0.69*EXP ((0.35*8.6) - 9.3))))

TDMIHP893 = pregheifers893*DMIPregH893 {kg DM/month}

DMIPregH78 = (DMIPregH7*(1+ ((7 - 8.6)*0.0025))) {kg DM/month}

TDMIHPreg78 = pregHeifers78*DMIPregH78 {Kg DM/month}

DMILactPregcows = DMILact {Kg DM/ month}

DOCUMENT: Dry mater intake of pregnant heifers

Total_preglact_cows = (preg_par1) + (Preg_par_2)+ (preg_par_3)+ (Preg_par_4)+
(preg_par_5)+ (preg_par_6) {cows}

TDMIlactpregcows = DMILactPregcows*Total_preglact_cows {kg DM/month}

DOCUMENT: Dry matter intake by lactating and pregnant cows

DMIWeaned_males = $\text{Body_W_steers}^{0.75} * (0.1493 * \text{NEmd} - 0.046 * \text{NEmd}^2 - 0.0196) * 30.4$
{KgDM /month}

TDMIS = DMIWeaned_males*Weaned_males {kg DM/month}

DMI_WHeifers = $((\text{BW_Weaned_H}^{0.75} * ((0.2435 * \text{NEmd}) - (0.0466 * \text{NEmd}^2) - 0.1128)) / \text{NEmd}) * 30.4$ {kg DM /month}

TDMI_WHeifers = DMI_WHeifers*Weaned_heifer_calves {Kg DM/month}

TotalDMI_Herd_deand =

TDMILact+DMIyearlings+TDMIDRY+TDMIdry2+TDMIHP7+TDMIHP893+TDMIHPreg
78+TDMIlactpregcows+TDMIS+TDMI_WHeifers {kg DM/month}

$\text{Total_herd_DD_per_Ha} = \text{TotalDMI_Herd_deand}/\text{Area} \text{ \{kg DM/ha\}}$
 $\text{TSC} = \text{Dry_Forage} + \text{Green_forage} \text{ \{kg DM\}}$
 $\text{RIF} = \text{GRAPH}(\text{TSC})$
 $(0.00, 0.1), (500, 0.6), (1000, 0.82), (1500, 0.9), (2000, 0.95), (2500, 1.00), (3000, 1.00)$
 $\text{RIF1} = \text{IF}(\text{RIF} > 1) \text{ THEN } (1) \text{ ELSE } (\text{RIF})$
DOCUMENT: Restricted intake of forage based on the available forage
 $\text{Actual_intake_per_ha} = \text{Total_herd_DD_per_Ha} * \text{RIF1}$
 $\text{Forage_growth} = (\text{Monthly_rainfall} * \text{Rain_use_effeciency}) \text{ \{kg DM /ha/month\}}$
 $\text{GFC} = (\text{Actual_intake_per_ha} * \text{PGFD}) \text{ \{kg DM/month\}}$
 $\text{SEN_in} = \text{IF}(\text{months} = 3) \text{ OR } (\text{months} = 4) \text{ OR } (\text{months} = 9) \text{ OR } (\text{months} = 10) \text{ THEN } (0)$
 $\text{ELSE } ((\text{Green_forage} - \text{GFC}) * \text{Senescence_rate}) \text{ \{kg DM/month\}}$
 $\text{Sen_Loss} = \text{SEN} * 0.2$
 $\text{SEN_out} = \text{SEN} - \text{Sen_Loss}$
DOCUMENT: Forage loss due to senescence
 $\text{DFC} = \text{Actual_intake_per_ha} - \text{GFC} \text{ \{kg DM/month\}}$
 $\text{Monthly_temperature} = \text{IF}(\text{months} = 1) \text{ THEN } (26.9) \text{ ELSE IF } (\text{months} = 2) \text{ THEN } (27.7)$
 $\text{ELSE IF}(\text{months} = 3) \text{ THEN } (27.1) \text{ ELSE IF}(\text{months} = 4) \text{ THEN } (27.1) \text{ ELSE}$
 $\text{IF}(\text{months} = 5) \text{ THEN} (26.1) \text{ ELSE IF}(\text{months} = 6) \text{ THEN } (26.7) \text{ ELSE IF}(\text{months} = 7)$
 $\text{THEN } (27.2) \text{ ELSE IF}(\text{months} = 8) \text{ THEN } (27.4) \text{ ELSE IF}(\text{months} = 9) \text{ THEN } (27.2)$
 $\text{ELSE IF}(\text{months} = 10) \text{ THEN } (26.2) \text{ ELSE IF}(\text{months} = 11) \text{ THEN} (25.6) \text{ ELSE}$
 $\text{IF}(\text{months} = 12) \text{ THEN } (26.1) \text{ ELSE } 0$
DOCUMENT: Monthly average temperature
 $\text{Dead rate} = 1 - \text{EXP}(-0.003077 * \text{Monthly rainfall}) + 0.0005 * \text{Monthly temperature}$
 $\text{Dry Forage litter} = \text{IF}(\text{months} = 4) \text{ OR } (\text{months} = 9) \text{ OR } (\text{months} = 10) \text{ THEN } (\text{Dry Forage})$
 $\text{ELSE } (\text{Dead rate} * (\text{Dry Forage} - \text{DFC})) \text{ \{Kg DM /ha/month\}}$
DOCUMENT: Decomposition of dry forage
 $\text{ANFC_IN} = \text{DFC} + \text{GFC} \text{ \{kgDM/month\}}$
 $\text{ANFC_OUT} = \text{IF}(\text{months} = 1) \text{ THEN } (\text{ANFC}) \text{ ELSE } (0) \text{ \{kgDM/year\}}$
 $\text{ANRF_IN} = \text{Monthly_rainfall} \text{ \{mm/month\}}$
 $\text{ANRF_OUT} = \text{IF}(\text{months} = 1) \text{ THEN } (\text{ANRF}) \text{ ELSE } (0)$

Dead_female_weaned_calves = LEAKAGE OUTFLOW
 LEAKAGE FRACTION = (Weaned_heifer_calves*Mortality_of_weaned_females)
 {cow}
 Growing_heifers = CONVEYOR OUTFLOW
 TRANSIT TIME = Growth_period
 ConcHeifers = (Replacement_heifers)*Conception rate {cows/month}
 DDMILact = DMILact/30.4 {Kg DM/day}
 MEcontent = (((DD*1000)-61)*0.011)+3.2/4.184 {Mcal/ha}
 NEcontent = (MEcontent +0.2473)/1.8315
 NEltotallact = DDMILact*NEcontent*RIF1 {Mcal/d}
 MEact_lact = ((0.006*DDMILact*((0.9 -GFDMD)*0.92)) + (0.05*1.5/
 ((0.002471*Green_forage)+3))) *BWLact/4.186 {Mcal/d}
 NEact_lact = (1.37*MEact_lact-0.138*MEact_lact²+0.0105*MEact_lact³-1.12)*0.5
 DOCUMENT: Metabolisable energy requirement for activity for lactating cows
 NEmaintLactCows = (0.96*BWLact^{0.75})*0.080 + (NEact_lact) {Mcal/ day}
 Document: Net energy requirement for maintenance of lactating cows
 NEBal_lact_cows = (NEltotallact-NEmaintLactCows) {Mcal/day}
 DOCUMENT: Net energy requirement available for production for lactating cows
 NE_in_milk = (0.386* MILKFat +0.205 *SNF + 0.236)/4.186 {Mcal/kg}
 MEL = (NE_in_milk*PMY1)
 MEL1 = IF (MEL=0) THEN (1) ELSE (MEL)
 MFRAC1 = NEBal_lact_cows/MEL1
 MFRAC11 = IF (MFRAC1>1) THEN (1) ELSE (MFRAC1)
 Yrday = MFRAC11*PMY1
 Jan_M_in = Yr_day
 DOCUMENT: Daily milk yield of cows that calved in January
 MSmilk1 = IF (MOL<9) THEN (MOL1) ELSE (0)
 MSmilk2 = IF (MOL2<9) THEN (MOL2) ELSE (0)
 MSmilk3 = IF (MOL_3<9) THEN (MOL_3) ELSE (0)
 MSmilk4 = IF (MOL_4<9) THEN (MOL_4) ELSE (0)
 MSmilk5 = IF (MOL_5<9) THEN (MOL_5) ELSE (0)

MSmilk6 = IF (MOL_6<9) THEN (MOL_6) ELSE (0)

MSmilk7 = IF (MOL_7<9) THEN (MOL_7) ELSE (0)

MSmilk8 = IF (MOL_8<9) THEN (MOL_8) ELSE (0)

MSmilk9 = IF (MOL_9<9) THEN (MOL_9) ELSE (0)

MSmilk10 = IF (MOL_10<9) THEN (MOL_10) ELSE (0)

MSmilk11 = IF (MOL_11<9) THEN (MOL_11) ELSE (0)

MSmilk12 = IF (MOL_12<9) THEN (MOL_12) ELSE (0)

DOCUMENT: Determines the months a cow is in milking depending on the month it calved

MOL1 = GRAPH (months)

(1.00, 1.00), (2.00, 2.00), (3.00, 3.00), (4.00, 4.00), (5.00, 5.00), (6.00, 6.00), (7.00, 7.00), (8.00, 8.00), (9.00, 9.00), (10.0, 10.0), (11.0, 11.0), (12.0, 12.0)

MOL2 = GRAPH (months)

(1.00, 12.0), (2.00, 1.00), (3.00, 2.00), (4.00, 3.00), (5.00, 4.00), (6.00, 5.00), (7.00, 6.00), (8.00, 7.00), (9.00, 8.00), (10.0, 9.00), (11.0, 10.0), (12.0, 11.0)

MOL_3 = GRAPH (months)

(1.00, 11.0), (2.00, 12.0), (3.00, 1.00), (4.00, 2.00), (5.00, 3.00), (6.00, 4.00), (7.00, 5.00), (8.00, 6.00), (9.00, 7.00), (10.0, 8.00), (11.0, 9.00), (12.0, 10.0)

MOL_4 = GRAPH (months)

(1.00, 10.0), (2.00, 11.0), (3.00, 12.0), (4.00, 1.00), (5.00, 2.00), (6.00, 3.00), (7.00, 4.00), (8.00, 5.00), (9.00, 6.00), (10.0, 7.00), (11.0, 8.00), (12.0, 9.00)

MOL_5 = GRAPH (months)

(1.00, 9.00), (2.00, 10.0), (3.00, 11.0), (4.00, 12.0), (5.00, 1.00), (6.00, 2.00), (7.00, 3.00), (8.00, 4.00), (9.00, 5.00), (10.0, 6.00), (11.0, 7.00), (12.0, 8.00)

MOL_6 = GRAPH (months)

(1.00, 8.00), (2.00, 9.00), (3.00, 10.0), (4.00, 11.0), (5.00, 12.0), (6.00, 1.00), (7.00, 2.00), (8.00, 3.00), (9.00, 4.00), (10.0, 5.00), (11.0, 6.00), (12.0, 7.00)

MOL_7 = GRAPH (months)

(1.00, 7.00), (2.00, 8.00), (3.00, 9.00), (4.00, 10.0), (5.00, 11.0), (6.00, 12.0), (7.00, 1.00), (8.00, 2.00), (9.00, 3.00), (10.0, 4.00), (11.0, 5.00), (12.0, 6.00)

MOL_8 = GRAPH (months)

(1.00, 6.00), (2.00, 7.00), (3.00, 8.00), (4.00, 9.00), (5.00, 10.0), (6.00, 11.0), (7.00, 12.0), (8.00, 1.00), (9.00, 2.00), (10.0, 3.00), (11.0, 4.00), (12.0, 5.00)

MOL_9 = GRAPH (months)

(1.00, 5.00), (2.00, 6.00), (3.00, 7.00), (4.00, 8.00), (5.00, 9.00), (6.00, 10.0), (7.00, 11.0), (8.00, 12.0), (9.00, 1.00), (10.0, 2.00), (11.0, 3.00), (12.0, 4.00)

MOL_10 = GRAPH (months)

(1.00, 4.00), (2.00, 5.00), (3.00, 6.00), (4.00, 7.00), (5.00, 8.00), (6.00, 9.00), (7.00, 10.0), (8.00, 11.0), (9.00, 12.0), (10.0, 1.00), (11.0, 2.00), (12.0, 3.00)

MOL_11 = GRAPH (months)

(1.00, 3.00), (2.00, 4.00), (3.00, 5.00), (4.00, 6.00), (5.00, 7.00), (6.00, 8.00), (7.00, 9.00), (8.00, 10.0), (9.00, 11.0), (10.0, 12.0), (11.0, 1.00), (12.0, 2.00)

MOL_12 = GRAPH (months)

(1.00, 2.00), (2.00, 3.00), (3.00, 4.00), (4.00, 5.00), (5.00, 6.00), (6.00, 7.00), (7.00, 8.00), (8.00, 9.00), (9.00, 10.0), (10.0, 11.0), (11.0, 12.0), (12.0, 1.00)

DOCUMENT: Months in lactation depending on the month the cows calved and the model simulation "cycle time"

IRC = 1/ (PKY*0.5*2.718281828)

PMY1 = MSmilk/ (IRC*EXP (0.5*MSmilk1))

DOCUMENT: Potential milk yield for cow calving in January (cows the calved in the other months of the year used s similar equation

FCM = (0.4*PMY1) + (15*(MILKFat/100)*PMY1) {kg/day}

DMILact1 = (0.1*FCM+0.025*BWLact)*30.4 {kg DM/month}

DOCUMENT: Dry matter intake of cows that calved in January (cows that calved in the other months of the year used equations similar to the above)

NEI_totallact2 = DMI2*NEcontent*RIF1 {Mcal/d}

NEBal_lact_cow_2 = (NEI_totallact2-NEmaintLactCows) {Mcal/day}

MEL2 = (NE_in_milk*PMY2)/0.82

MEL21 = IF (MEL2=0) THEN (1) ELSE (MEL2)

MFRAC2 = NEBal_lact_cow_2/MEL21

MFRAC21 = IF (MFRAC2>1) THEN (1) ELSE (MFRAC2)

Yrd2 = MFRAC21*PMY2

Document: Actual daily milk yield for cows the calved in February (cows that calved in the other months of the year used a similar equation).

Calving_heifers = CONVEYOR OUTFLOW

Cal_par_1 = CONVEYOR OUTFLOW

Cal_par_2 = CONVEYOR OUTFLOW

cal_par_3 = CONVEYOR OUTFLOW

cal_par_4 = CONVEYOR OUTFLOW

cal_par_5 = CONVEYOR OUTFLOW

CALV = Initial value (calving heifers + Cal_par_1 + Cal_par_2 + Cal_par_3 + cal_par_4 + cal_par_5) {cows}

DOCUMENT: Total number of calves born

IJAN = INT (IF (months=1) THEN (CALV) ELSE (0))

IFEB = INT (IF (months=2) THEN (CALV) ELSE (0))

IMAR = INT (IF (months=3) THEN (CALV) ELSE (0))

IAPR = INT (IF (months=4) THEN (CALV) ELSE (0))

IMAY = INT (IF (months=5) THEN (CALV) ELSE (0))

IJUN = INT (IF (months=6) THEN (CALV) ELSE (0))

IJUL = INT (IF (months=7) THEN (CALV) ELSE (0))

IAUG = INT (IF (months=8) THEN (CALV) ELSE (0))

ISEP = INT (IF (months=9) THEN (CALV) ELSE (0))

IOCT = INT (IF (months=10) THEN (CALV) ELSE (0))

NOV = INT (IF (months=11) THEN (CALV) ELSE (0))

IDEC = INT (IF (months=12) THEN (CALV) ELSE (0))

DOCUMENT: Total number of calves born in a given month

OJan = IF (months=9) THEN (JANcow) ELSE (0)

OFEB = IF (months=10) THEN (FEBcow) ELSE (0)

OMAR = IF (months=11) THEN (MARcow) ELSE (0)

OAPR = IF (months=12) THEN (APRcow) ELSE (0)

OMAY = IF (months=1) THEN (MAYcow) ELSE (0)

OJUN = IF (months=2) THEN (JUNcow) ELSE (0)

OJUL = IF (months=3) THEN (JULcow) ELSE (0)

OAUG = IF (months= 4) THEN (AUGCOW) ELSE (0)
 OSEPT = IF (months=5) THEN (SEPCOW) ELSE (0)
 IOOCT = IF (months=6) THEN (OCTCOW) ELSE (0)
 ONOV = IF (months=7) THEN (NOVCOW) ELSE (0)
 ODEC = IF (months=8) THEN (DECCOW) ELSE (0)
 DOCUMENT: Signal to the end of lactation depending on the when a cow calved
 and tracks the number of cows that calved in a particular months
 JANYr_day = JANcow*Yr_day {kg/day}
 FEB_Yr_day = FEBCOW*Yrd2 {kg/day}
 MAR_Yr_day = MARCOW*Yrd3 {kg/day}
 APR_Yr_day = APRCOW*Yrd4 {kg/day}
 MAY_Yr_day = MAYCOW*Yrd5 {kg/day}
 JUN_Yr_day = JUNCOW*Yrd6 {kg/day}
 JUL_Yr_day = JULCOW*Yrd7 {kg/day}
 AUG_Yr_day = AUGCOW*Yrd8 {kg/day}
 SEP_Yr_day = SEPCOW*Yrd9 {kg/day}
 OCT_Yr_day = OCTCOW*Yrd10 {kg/day}
 NOV_Yr_day = NOVCOW*Yrd11 {kg/day}
 DECYr_day = DECCOW*Yrd12 {kg/day}
 DOCUMENT: Total daily milk yield of cows that calved in a particular month
 MCdeaths = LEAKAGE OUTFLOW
 LEAKAGE FRACTION = Weaned_males*mortality_weaned_males {cow/month}
 DOCUMENT: Number of males calves that died
 Growing_steers = CONVEYOR OUTFLOW
 TRANSIT TIME = growth_period_2
 Steers_sold = Yearling_steers
 Dead_par_6 = LEAKAGE OUTFLOW
 LEAKAGE FRACTION = Par_6_cows*Cow_mortality_rate {cows}
 Conc_par_6 = CONVEYOR OUTFLOW
 TRANSIT TIME = months_open
 Culled_cows = IF (months=5) or (months=11) THEN (preg_par_6) ELSE (0)

DOCUMENT: Old cows were culled in the month of May and November

ANFP_IN = Forage_growth {KgDM/ha/month}

ANFP_OUT = IF (months=1) THEN (ANFP) ELSE (0) {Kg Dm/year}

TLU = (PregHeifers7*0.6)+ (pregHeifers78*0.6)+ (Weaned_heifer_calves*0.6)+

(Weaned males*0.6)+(Yearling steers*0.6)+

(TotalpregDry_cows*1.2)+(Total_pregdry_cows2*1.2)+(Total_preglact_cows*1.2)+(To

tlact_nonpreg*1.2)+(Female calves*0.25)+(male calves*0.25)+(Replacement

heifers*0.6)

Drug_cost = Drug_cost_per_TLU*TLU

Labour_cost = Labour_cost_per_TLU*TLU

Drench = Drench_cost_per_TLU*TLU

Acariside_cost = Acariside_cost_per_TLU*TLU

Mlnearal_lick_cost = Minera_link_cost_per_TLU*TLU

Cow_income = culled_cows*Price_of_cows

HerdTestday_mily_yield = SUM (APR_Yr_day, AUG_Yr_day, DEC_Yr_day,

FEB_Yr_day, JAN_Yr_day, JUL_Yr_day, JUN_Yr_day, MAR_Yr_day, MAY_Yr_day,

NOV_Yr_day, OCT_Yr_day, SEP_Yr_day)

Monthly_Herd_milk_yield = HerdTestday_mily_yield*30.4

Milk_price = If (months = 12) OR (months=1) OR (months=2) OR (months=6) OR

(months=7) OR (months = 8) THEN (300) ELSE (180)

Milk_income = Monthly_Herd_milk_yield*Milk_price

Steer_income = Steers_sold*Steer_price

Income = Cow_income+Milk_income +Steer_income

Var_cost = Drug_cost+labour_cost+Drench+Acariside_cost+Mlnearal_lick_cost

Month_income = Income-Var_cost

Ann_Income_IN = Month_income

Ann_Income_OUT = IF (months=1) THEN (Annual_income) ELSE (0)

AN_MLK_In = Monthly_Herd_milk_yield

AN_MLK_Out = IF (months= 1) THEN (Ann_Milk) ELSE (0)

Female_calves_deaths = LEAKAGE OUTFLOW

LEAKAGE FRACTION = (Female_calves*Female_cal_Mort_rate) {cow/month}

Weaning_Female_calves = CONVEYOR OUTFLOW
 TRANSIT TIME = Weaning_age
 pregn6 = CONVEYOR OUTFLOW
 TRANSIT TIME = gestationh7 {months}
 FML_Nursing_calve = CALV*0.5 {cows/month}
 Male_calves_deaths = LEAKAGE OUTFLOW
 LEAKAGE FRACTION = male_calves*Macal_Mort_rate
 Weaning_male_calves = CONVEYOR OUTFLOW
 TRANSIT TIME = Weaning_age
 Male_Nursing_calve = CALV*0.5 {cows/month}
 Dead_par_1 = LEAKAGE OUTFLOW
 LEAKAGE FRACTION = Par_1*Mort_rate {cows}
 Conc_par_1 = CONVEYOR OUTFLOW
 TRANSIT TIME = months_open
 drying_par_12 = CONVEYOR OUTFLOW
 drying_par1 = CONVEYOR OUTFLOW
 dead_par_2 = LEAKAGE OUTFLOW
 LEAKAGE FRACTION = Par_2_cows*Cow_mortality_rate {cows}
 Conc_par_2 = CONVEYOR OUTFLOW
 TRANSIT TIME = months_open
 drying_par22 = CONVEYOR OUTFLOW
 drying_par_2 = CONVEYOR OUTFLOW
 Dead_par_3 = LEAKAGE OUTFLOW
 LEAKAGE FRACTION = Par_3_cows*Cow_mortality_rate {cows}
 Conc_par_3 = CONVEYOR OUTFLOW
 TRANSIT TIME = months_open
 drying_par_3 = CONVEYOR OUTFLOW
 drying_par32 = CONVEYOR OUTFLOW
 Dead_par_4 = LEAKAGE OUTFLOW
 LEAKAGE FRACTION = Par_4_cows*Cow_mortality_rate {cows}
 Conc_par_4 = CONVEYOR OUTFLOW

TRANSIT TIME = months_open
 drying_par_42 = CONVEYOR OUTFLOW
 drying_par_4 = CONVEYOR OUTFLOW
 Conc_par_5 = LEAKAGE OUTFLOW
 LEAKAGE FRACTION = months_open
 drying_par52 = CONVEYOR OUTFLOW
 drying_par_5 = CONVEYOR OUTFLOW
 pregh893 = CONVEYOR OUTFLOW
 TRANSIT TIME = gestationh78 {months}
 IFEB_M = IF (months=2) THEN (CALV*0.5) ELSE (0)
 IJAN_M = IF (months=1) THEN (CALV*0.5) ELSE (0)
 IMAR_M = IF (months=3) THEN (CALV*0.5) ELSE (0)
 IAPR_M = INT (IF (months=4) THEN (CALV*0.5) ELSE (0))
 IMAY_M = INT (IF (months=5) THEN (CALV*0.5) ELSE (0))
 IJUN_M = INT (IF (months=6) THEN (CALV*0.5) ELSE (0))
 IJUL_M = INT (IF (months=7) THEN (CALV*0.5) ELSE (0))
 IAUG_M = INT (IF (months=8) THEN (CALV*0.5) ELSE (0))
 ISEP_M = INT (IF (months=9) THEN (CALV*0.5) ELSE (0))
 IOCT_M = INT (IF (months=10) THEN (CALV*0.5) ELSE (0))
 INOV__M = INT (IF (months=11) THEN (CALV*0.5) ELSE (0))
 IDEC_M = INT (IF (months=12) THEN (CALV*0.5) ELSE (0))
 DOCUMENT: Number of calves born in a particular month
 SR = Area/TLU
 CBW = 0.06275*MW {kg}
 DOCUMENT: Calf body weight
 CW = 18+ ((DOG - 280)*0.665)*CBW/45 {kg}
 DOCUMENT: Conceptus body weight
 DNED = 0.086*((0.96*BWDry)-CW)^{0.75}
 Total_Preg_heifers = PregHeifers7+ pregHeifers78+ pregheifers893+
 Weaned_heifer_calves {cows}
 DDMI PregH78 = DMIPregH78/30.4 {kg DM/day}

$DDMI_WHeifers = DMI_WHeifers/30.4 \text{ {kg DM/day}}$
 $DDMIWeaned_males = DMIWeaned_males/30.4 \text{ {kg DM/day}}$
 $SBWWeaned_males = 0.96*Body_W_steers \text{ {kG}}$
 $DNEmaintWeaned_males = 0.086*(SBWWeaned_males)^{0.75} \text{ {Mcal/day}}$
 $growth_time = time$
 $NEItotal_H = DMI_WHeifers*NEcontent *RIF1 \text{ {Mcal/month}}$
 $SBWH = 0.96*BW_Weaned_H \text{ {Kg}}$
 $MEActH = ((0.006*DDMI_WHeifers*((0.9-GFDMD)*0.92)) + (0.05*1.5/$
 $((0.002471*Green_forage)+3)))*BW_Weaned_H/4.186 \text{ {Mcal/d}}$
 $NEActH = (1.37*MEActH-0.138*MEActH^2+0.0105*MEActH^3-1.12)*0.5$
 $NEmaintH = (0.086*(SBWH)^{0.75} + NEActH)*30.4 \text{ {Mcal/ month}}$
 $NEBalance_heifer = NEItotal_H-NEmaintH \text{ {Mcal/day}}$
 $NE_Hgrowth = NEBalance_heifer$
 $Weight_EBW_H = (0.91*Wheifers*550)/Adult_weight_cow \text{ {kg}}$
 $GR1 = NE_Hgrowth/ (27.14*0.2788/Weight_EBW_H^{0.1107}+45.20 * 0.0039388 *$
 $Weight_EBW_H^{0.788})$
DOCUMENT: Growth rate of heifers
 $Growth_rate_H = IF (growth_time < 18) THEN GR1 ELSE (Gr)$
 $TRANSIT_TIME = Par_5_cows*Cow_mortality_rate \text{ {cows}}$
 $growth_time_1 = time$
 $NEItotal_ST = NEcontent*DDMIWeaned_males*RIF1 \text{ {Mcal/month}}$
 $MEactWeaned_males = ((0.006*DDMIWeaned_males*((0.9-GFDMD)*0.90)) +$
 $(0.05*1.5/ ((0.02471*Green_forage)+3)))*SBWWeaned_males/4.186 \text{ {Mcal/d}}$
 $NEactWeaned_males = (1.37*MEactWeaned_males-$
 $0.138*MEactWeaned_males^2+0.0105*MEactWeaned_males^3-1.12)*0.5$
 $NEactWEM = IF (NEactWeaned_males < 0) THEN (0) ELSE (NEactWeaned_males)$
 $NEmaintWeaned_males = (DNEmaintWeaned_males+NEactWEM)*30.4 \text{ {Mcal/month}}$
 $NEBalance_Steer = NEItotal_ST-NEmaintWeaned_males \text{ {Mcal/month}}$
 $NE_STgrowth = NEBalance_Steer \text{ {Mcal/ month}}$
 $Weight_EBW = (0.91*Body_W_steers*550)/Adult_weight_bull \text{ {kg}}$

Growth_rate = IF (growth_time_1<18) THEN (NE_STgrowth/
 $(20.06 \cdot 0.2788 / \text{Weight_EBW}^{0.1107} + 33.41 \cdot 0.0039388 \cdot \text{Weight_EBW}^{0.788})$) ELSE (0)
 {kg/month}

DOCUMENT: Growth rate of steers

BWPreg = BWLact

NEactlactpreg = $((0.006 \cdot \text{DDMILact} \cdot (0.9 \cdot \text{GFDMD} \cdot 0.92)) + (0.05 \cdot 1.5 /$
 $((0.002471 \cdot \text{Green_forage}) + 3))) \cdot \text{BWPreg} / 4.186$ {Mcal/d}

MEactHP = $((0.006 \cdot \text{DDMIPregH78} \cdot ((0.9 - \text{GFDMD}) \cdot 0.92)) + (0.05 \cdot 1.5 /$
 $((0.002471 \cdot \text{Green_forage}) + 3))) \cdot \text{BWHP7} / 4.186$ {Mcal/d}

NEactHP = $(1.37 \cdot \text{MEactHP} - 0.138 \cdot \text{MEactHP}^2 + 0.0105 \cdot \text{MEactHP}^3 - 1.12) \cdot 0.5$

NEPreg = $((0.00318 \cdot \text{DOG} - 0.0352) \cdot (\text{CBW} / 45)) / 0.218 \cdot 30.4$ {Mcal/month}

MEactDRy = $((0.006 \cdot \text{DDMIDRY} \cdot ((0.9 - \text{GFDMD}) \cdot 0.92)) + (0.05 \cdot 1.5 /$
 $((0.002471 \cdot \text{Green_forage}) + 3))) \cdot \text{BWDry} / 4.186 \cdot 0.5$ {Mcal/d}

NEact_dry = $(1.37 \cdot \text{MEactDRy} - 0.138 \cdot \text{MEactDRy}^2 + 0.0105 \cdot \text{MEactDRy}^3 - 1.12) \cdot 0.5$

NEmaitDry = $(\text{DNED} + \text{NEact_dry}) \cdot 30$ {Mcal/month}

TotalRNE_Dry = $\text{NEmaitDry} + \text{NEPreg}$ {Mcal/month}

SBWHP = $0.96 \cdot \text{BWHP7}$ {Kg}

NEManitHPreg = $(0.086 \cdot (\text{SBWHP} - \text{CW})^{0.75} + \text{NEactHP}) \cdot 30.4$ {Mcal/ month}

TotalNERheiferPreg = $\text{NEManitHPreg} + \text{NEPreg}$ {Mcal/ month}

NEmaintPreg_Cows = $((0.096 \cdot \text{BWPreg})^{0.75} \cdot 0.08 + \text{NEactlactpreg}) \cdot 30.4$
 {Mcal/month}

Sell_rate_heifer = IF (SR<SRControl) THEN $((\text{SRControl} - \text{SR}) / \text{SRControl})$ ELSE (0)

DOCUMENT: Rate at which the excess heifers were sold (cow/month)

TDMyaerlings = $\text{Yearling_steers} \cdot \text{DMlyearlings}$

NEltotallactpreg = $\text{NEcontent} \cdot \text{DMILactPregcows} \cdot \text{RIF1}$ {Mcal/d}

NEBalanceLactPreg = $\text{NEltotallactpreg} - \text{NEmaintPreg_Cows}$

NEltotalDry = $\text{DMIDRY} \cdot \text{NEcontent} \cdot \text{RIF1}$ {Mcal/month}

NEBalanceDry = $(\text{NEltotalDry} - (\text{NEmaitDry} + \text{NEPreg}))$ {Mcal/month}

NEltotalHP = $\text{DMIPregH78} \cdot \text{NEcontent} \cdot 30.4 \cdot \text{RIF1}$ {Mcal/d}

NEBalanceHP = $(\text{NEltotalHP} - (\text{NEManitHPreg} + \text{NEPreg}))$ {Mcal7d}

Janlact_yld = $\text{JanMin_out} \cdot 30.4$ (kg/month)

DOCUMENT: Lactation milk yield for cows that calved in January (similar equation was used for the rest of the months)