A MODEL FOR ADAPTIVE LIVESTOCK MANAGEMENT ON SEMI-ARID RANGELANDS IN TEXAS

A Dissertation

by

SIKHALAZO DUBE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2005

Major Subject: Rangeland Ecology and Management

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May 2005

Rangeland Ecology and Management

ABSTRACT

A Model for Adaptive Livestock Management on Semi-Arid Rangelands in Texas.

(May 2005)

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A stochastic, compartmental Model for Adaptive Livestock Management (MALM) was developed for cow-calf enterprise for Rolling Plains of Texas from an existing model, Simple Ecological Sustainability Simulator (SESS). The model simulates forage and animal production. It runs on a monthly time step. Two stocking strategies, flexible and fixed, were evaluated at seven stocking levels for effects on forage and animal production, range condition, and net ranch income. Evaluation data were obtained from published and unpublished data from Texas A&M Agricultural Experimental Station at Vernon for Throckmorton.

The model adequately simulated forage and animal production. Light fixed stocking rates and flexible stocking strategies resulted in cows of median body condition score (BCS) 5, compared to low BCS of 4 under moderate fixed stocking rate, and BCS of 3 under heavy fixed stocking. BCS declined from autumn to early spring and peaked in summer. Cows under light fixed stocking rates and under flexible stocking were heavier (460 kg) compared to those under heavy fixed stocking (439 kg). Replacement rates were lower under light stocking (22 %), compared to flexible (37 %) and heavy stocking (56 %). Calf crops were all above the reported 90 % expected for bred heifers because of the replacement policy.

Flexible stocking strategy resulted in higher net income (\$19.62 ha^{-1}), compared to fixed light (\$5.93 ha^{-1}) or fixed heavy (\$-17.35 ha^{-1}) stocking strategies. Coefficient of variation (CV) in net income was highest under heavy stocking (90%) compared to light stocking (60%) and flexible stocking (50%). Maximum net income was obtained between 0.05 AUM·ha^{-1} and 0.13 AUM·ha^{-1} when fixed stocking strategy was used but when flexible stocking strategy was used maximum net income was obtained between 0.1 AUM·ha^{-1} and 0.17 AUM·ha^{-1}.

Range condition rapidly declined under fixed heavy stocking, increased under fixed and light flexible stocking, and remained constant under moderate flexible stocking. Heavy fixed stocking decreased range condition rapidly over a 20-year period.

MALM was an effective tool to demonstrate effects of different management strategies. The model can function as a strategic or a tactical decision aid. It is concluded that there is potential for this model to assist managers in improving the sustainability of agriculture.

DEDICATION

This dissertation is dedicated to my dear parents, Michael and Melina, who gave me the greatest gift, life. My sisters and brothers: Sindile, Ellah, Shepard, Esau M. and Jacob M., who have in various ways supported my academic career. To my wife, Elizabeth, and daughter, Melina, whose love and devotion has been the pillar of support all these years.

To God be the Glory, Great Things He Hath Done

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As a young man growing up in Africa, my father was an avid country music fan and every once in a while he would sport his cowboy hat and tell me about cowboys from Texas although he has never been to Texas. As a high school student studying biology, I had the pleasure of meeting a molecular biologist, Dr. Joseph M. Gopo, who studied at East Texas State University in the early 1970s. He spoke nostalgically about Texas universities and about the leader in agriculture, Texas A&M University. He would later become my biology professor. When my family and I finally landed in Texas in 2002, we found out that both my father and Joseph were right about the warmth and welcoming nature of Texans based on their love of country music and from living in Texas. I am grateful to the many people I have met in Texas who have been kind to me and my family. I will not mention in this document those names for fear of missing some. Thank you, Texas.

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Last but not least, I would like to thank the staff and faculty of the Department of Rangeland Ecology and Management. The staff helped with the details on financial documents, letters, and reminders on deadline, coffees, paper and everything that I ever needed. You all made my studies a pleasure.

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CHAPTER I

INTRODUCTION

The two major constraints that affect ranching in semi-arid rangelands are drought and uncertain market prices. Ranchers are often concerned with the variability of prices and production (Weersink et al. 2002, Pannell and Glenn 2000). Management decisions are evaluated against a scenario of uncertainty in climate and seasonal prices for animal products. Drought is an inevitable part of normal climate fluctuations (Thurow and Taylor, 1999). Animal production depends heavily on forage produced, which depends on rainfall.

Ranchers make decisions based on two main goals: 1) to stay in business despite changes in product prices, weather, policy, advances in technology and social conditions; 2) to increase wealth over time (Pannell and Glenn 2000). In keeping with these goals, ranchers are concerned with getting key decisions right, e.g. purchasing land and equipment, performing resource improvements at the right time, and making correct strategic and tactical decisions such as stocking rate adjustment. Considering the limited forecasting power within climatology, the best management options under climatic and economic variability remain those geared towards rapid and efficient response to the risk. Manipulation of stock numbers and improved feeding strategies with the aim of reducing operation costs. Timing is everything in ranching. Models should, therefore, reflect these concerns. Ranch budget models are valuable in decision-making because

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This thesis follows the style of Journal of Range Management.

they recognize relevant characteristics of the business such as enterprise interactions, resource constraints, expert knowledge, personal preferences, attitudes and competence. Emphasis should be placed on development of a simulation model that couples plant-growth and animal production with economic decisions. Such a decision tool will appeal to managers and have the opportunity for widespread use and acceptance. Existing systems have not been suitable for this type of decision support. Diaz-Solis et al. (2003), recognizing the need for such a model, utilized an adaptive approach in the development of Simple Ecological Sustainability Simulator (SESS), a model that incorporates the manager's input in terms of observations and experience.

Droughts are expected to lower net income significantly as variable costs for inputs such as feed increase. As stocking rate increases, production per animal will decrease as competition for resources and production costs become limiting but production per acre will exhibit a quadratic response initially increasing before declining. In general, producers are expected to produce at stocking rates where total revenue is equal to or above total costs (McGuigan et al. 2002). Figures 1 and 2 illustrate the impact of stocking rate on production per animal, and changes in expenditure and income, respectively. In Figure 2 variable costs increase slowly with increase in stocking rate at the same time as the gross returns increase. The increase only last up to B, after which an increase in variable costs is exponential, resulting in decrease in gross returns. This illustrates that there is a window of opportunity, region AB, during which an increase in stock numbers is beneficial. Within this production zone an increase in stock numbers results in the spreading of operation costs among production units. However, further increase in stock numbers beyond this point results in high variable costs which, cannot be absorbed among the animals.

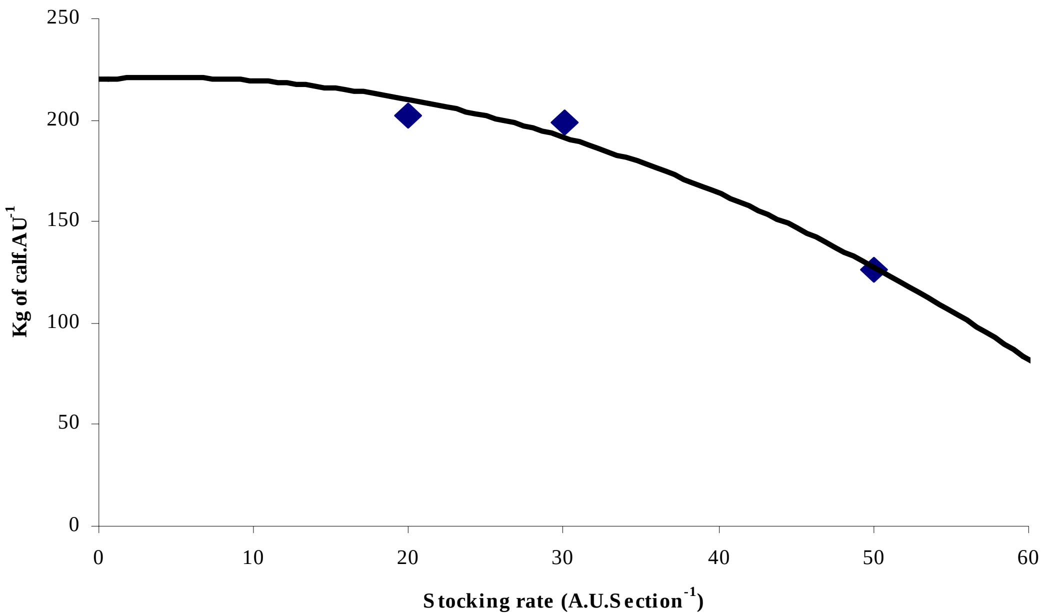

Figure 1. An illustration of the relationship between stocking rate and calf weight produced per animal unit (modified from Kothmann et al. 1971).

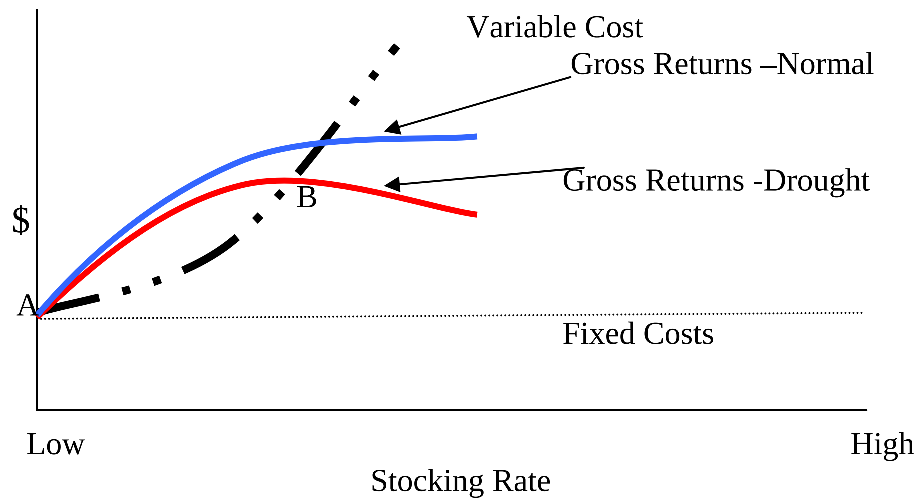

Figure 2. Illustration of economic returns during drought and normal years (source, modified from Workman. 1986).

Problem statement

Over the years, the ability of ranchers in semi-arid rangelands to depend solely on ranch income has diminished. Uncertainty in prices of products, high cost of inputs and frequent droughts threaten the sustainability of livestock enterprises and rangeland health worldwide (Herne 1998). Science continues to build complex ecological and economic decision models that, while well intentioned, do not find a large audience among the ranching community. Many decision models having a high level of organizational structure and resolution, cannot be easily parameterized for new locations, and do not allow for adaptive changes in operations within simulation periods as it may become necessary to reduce the nature and extent of risk (e.g., persistent drought or sudden price changes).

Decision tools should be of a level of organization and resolution that is user-friendly and should utilize the rancher’s production and management parameters and experience/knowledge. To this end, initial work has been conducted (e.g. Díaz-Solis et al. 2003, Pannell and Glenn 2000; Lemberg et al. 2002, Cacho et al.1999, Thompson and Powell 1998, Kreuter et al. 1996, Whitson et al. 1982).

The work of Díaz-Solis et al. (2003) addressed the subject of a simple decision tool in developing SESS; however, the research did not include the economics of ranching. For example a number of important animal parameters (e.g. mortality of both cow and calf) were missing in SESS. Further development of this model to refine the parameters and include economic analysis at the enterprise level was the objective of this study.

An adaptive decision tool is vital for sustainable livestock production in semi-arid rangelands. Ranchers most likely to remain productive despite the uncertainties are those who practice adaptive management based on sound data collection and analyses. Poor decisions, such as delayed selling in the face of a drought, and continuous overstocking can be costly for ranchers. Strategies available to ranchers in Australia, which can minimize economic losses and degradation in semi-arid rangelands, include light and variable stocking (O'Reagain et al. 2003). These can be relevant for Texas ranchers. Light stocking entails "safe" levels of forage utilization. Using this strategy a rancher can go through most droughts without feeding extra forage or making extensive shifts in management activities. However, they may miss the opportunity for exploiting forage produced in above average seasons. Variable stocking strategy involves closely monitoring forage production and altering stocking rate to adjust forage demand to the level of forage produced. While this strategy ensures maximum utilization of forage, it is costly and risky in terms of management, it involves extensive management activity, such as increases in labor input and transportation cost to adjust stocking rate.

Objectives

The broad objective of this study was to evaluate stocking strategies using a simple simulation model and to determine optimal management strategies to sustain range condition and optimize ranch net income in semi-arid rangelands in north central Texas.

The specific objectives were:

1. To modify and utilize the SESS model (Díaz-Solis et al. 2003) to simulate the response of animal production under stocking rate management strategies for the Rolling Plains region of Texas.
2. To evaluate the effects of stocking rate for fixed and flexible strategies on range condition, ranch income and expenses for a cow-calf enterprise for the Rolling Plains region of Texas.

CHAPTER II

LITERATURE REVIEW

Forage production

Sims and Singh (1978a, b) working on 10 western North American grasslands found annual net primary production (ANPP) was linearly related to precipitation up to 500 mm·year^{-1}. In the 10 grasslands studied, when grazing was a factor the linear relationship could occur up to 800 mm·year^{-1}. Lauenroth and Sala (1992) found a linear relationship between both seasonal and annual precipitation and annual net primary production. They also found a lag response of forage production to fluctuations in precipitation spanning several years. Based on their findings, we used a linear relationship between ANPP and precipitation.

Senescence

Senescence in plants occurs part by part as individual leaves and stems age (Blackburn and Kothmann 1989). Woodward and Wake (1994) using differential equations found that grass senescence was explicitly dependent on the age of the leaf. Because senescence in plants is difficult to measure directly, Bircham and Hodgson (1983) estimated senescence loss by marking and measuring leaves on tillers. A number of studies have found the age of the pasture to be an important determinant of senescence (Trippi 1989, Noodén 1988, Leopold 1980). Blackburn and Kothmann (1989) derived a daily senescence rate as a function of age, where age was defined by the amounts of current forage growth and previous green pool and previous age of the green forage pool.

Stocking rate decisions

The interaction of grazing and climate significantly alters the productivity of many semi-arid rangelands. The success of any livestock enterprise will depend on the ability of management to cope with the extreme fluctuations in forage supply as consequence of erratic precipitation. Apart from coping with forage fluctuation ranchers have to cope with market price fluctuations for livestock products. Failure to cope can result in over or under-utilization of forage resources resulting in both ecologically and economically unsustainable livestock enterprises (O'Reagain et al. 2003). A delayed reaction to reduced forage growth can lead to substantial economic losses as ranchers purchase more feed and/or sell livestock at depressed market prices during droughts (Torell et al. 1991).

The challenge in livestock production is to reduce livestock numbers as forage becomes limiting and increase numbers when forage production increases. Stocking rate is, therefore, key in grazing management (Gillen and Sims 2004).

Stocking strategies

Economic and environmental sustainability depends largely on the ability of management to adapt a stocking rate strategy that minimizes economic loss while maintaining or improving range condition. O'Reagain et al. (2003) defined and characterized the three stocking strategies as follows.

1. **Light fixed stocking** utilizes a safe amount of forage determined as certain proportion of forage growth. Scanlan et al. (1994) suggests utilization of between 15-25% of average annual forage produced. Use of this strategy minimizes over-grazing, relegating heavy use to a few periods of severe droughts. The resource base is accorded ample time to recover after a drought and perennial species are maintained or increased in the grazing areas (O'Reagain et al. 2003). Production per unit area is low but individual animal productivity is high (Sansoucy 1995) Light stocking has minimum variable production costs because in low forage production years, cost of feed is minimized.
2. **Flexible or variable stocking** takes into account inter-annual variation in forage production. It allows for determining decision points and using these periods to match animal numbers to forage supply. Skills in estimating production potential and onset of production in an area and adjusting animal numbers to match demand to the amount of standing forage at key times are vital. Forage demand for each animal is calculated for the period between decision-periods with a buffer assumed to cushion late onset of next forage production period.

   Use of this strategy takes advantage of intra-seasonal forage production peaks and maximizes use of forage production. Due to greater forage-use, animal production per unit area is higher than under light stocking. This method requires frequent adjustment to the herd-size, which would increase production cost.

Many producers do not adjust animal number frequently because of the impact on production cost alluded to above.

3. **Heavy fixed stocking** involves stocking a grazing area with constant high number of animals. It is oblivious of the intra and inter-seasonal variation in forage production. The assumption is that high stock numbers are economically viable as production per area is higher. In periods of droughts, feed is bought to maintain the stock numbers. This strategy has often been blamed for observed and perceived rangeland degradation in semi-arid and arid rangelands. High stock numbers are common in societies where livestock are kept for multi-purpose use, and marketing is low a priority (Behnke 1985).

    Heavy fixed stocking is impacted by even moderate droughts. Average production per unit area is generally higher than with light fixed stocking leading to a false sense of economic gain. The major variable production costs are associated with supplementary feeding, increased herd replacement rate, and degradation of the range. The former is a direct short-term cost which is readily perceived. The latter is a delayed long-term cost which is rarely accounted for in planning.

Body condition score and animal weight

Body Condition Scoring (BCS) is a rapid, subjective visual tool that livestock and wildlife managers use to evaluate health, and assess nutritional status of animals in an effort to manage for optimum production (Kunkle et al. 1994). BCS is based on the amount of body reserves an animal possess in fat and muscles.

Done with skill and at critical times in the reproductive circle of an animal, this tool can assist in managing nutritional needs of an animal. A BCS of 5 on a 1-9 scale is considered optimal at breeding, and is recommended for breeding animals to increase conception rate and weaned calf crop.

BCS is a more reliable indicator of nutritional status than animal weight which does not consider frame score and body size. BCS provides a rough guide of the nutritional adequacy of the diet and the level of food intake of an animal (Kertz et al. 1997). It further allows managers in the field to group animals by nutritional need, making management more efficient.

Characteristics of a cow-calf enterprise

The goal in a cow-calf enterprise is to sell a calf from every cow that is exposed to a bull. Management strategies employed in the enterprise affect calf crop and consequently income from the enterprise (Knight et al. 1990; Kothmann et al. 1970). The size of the operation is also important as it determines the extent to which fixed costs can be spread through the production units (Langemeier et al. 1994). Most operations, after accounting for mortality and failure of cows to breed, realize at least 85% calf crop annually (Forero et al. 2004). The cow-calf production sector is comprised of part-time and recreational, and business oriented producers (McGrann 1997, Broadworth et al. 1993). Part-time and recreational producers often have the bulk of their livelihood based on income from sources other than their cow-calf enterprise. The business producers sustain their business and livelihood from incomes derived from the marketing of the cow-calf products.

Producers are drawn to the cow-calf production sector for a variety of reasons. Broadworth et al. (1993) outline the following advantages as the main reasons; the enterprise is perceived to require low labor inputs; does not require intensive management, thus can be managed at family level with basic livestock management knowledge; there is limited requirement for specialized buildings as would be the case in dairy, feedlot and poultry production; animals can utilize roughage of low protein content, thus animals can be finished on rangelands; and cow-calf enterprise can be run in conjunction with other ranch enterprises.

The limitations of a cow-calf enterprise are recognized as: generally low net returns; seasonality of income; production units often are small; in geographic areas where high capital investment is required, the economics limit expansion; and the cow-calf enterprise requires year-round attention.

In a cow-calf enterprise, the production unit is the whole herd which comprises the pregnant and open cows, calves, and replacement heifers, and male animals (Fitzhugh et al. 1975). The individual cattle classes have different nutritional requirements and interact with other classes making the management of such an enterprise difficult (Cartwright 1970). Thiessen et al. (1984) stated that for a cow to produce a salable calf, feed requirement during the period of attachment to the calf constitutes between 50-80% of total requirement.

The cow-calf sector faces unprecedented challenges in Texas where it is losing its market share to pork and chicken (McGrann 1997). Due to loss of market share to other commodities, price increases would not necessarily curtail decline of financial returns. The part-time or recreational producers who account for about 91% of the herds in Texas are the ones most affected by the loss in market share (NBCA 1997). To meet this challenge and stay in production, producers in the cow-calf sector have to work harder to minimize production costs. New technologies and production strategies need to be developed and assessed.

The other major challenge in cow-calf enterprises, apart from the feed requirement limitations, is deciding whether or not to raise replacements within the herd or purchase replacements. The consequences of such a decision have both biological and economic implications. Raising replacement heifers has the advantages of knowing the sires of the heifer and thus the genetic potential (Zollinger and Carr 1993). Also the disease status of heifers raised from the herd is often known and appropriate treatments applied. The disadvantages are that it takes longer before the heifers can start producing calves which means the related costs often out weight the eventual revenues that will be realized once they start breeding, if they breed.

Purchase of pregnant replacement heifers has the advantage that the conception chances of the heifers are often known, since they are bought pregnant. Costs associated with early requirements prior to first pregnancy are often not met by the purchaser. The disadvantages are that there is often limited knowledge on the genetic potential and disease associated with the heifers, especially genetic diseases (Lacy 2004). Bought heifers can, therefore, potentially affect the future productivity of the operation should any bred heifer be infected with a major livestock disease.

Key to the potential economic benefits in a cow-calf enterprise are production levels, reproduction, and use of capital and control of production costs (Lacy 2004). Production refers to numbers and weights of salable calves and cows. If more animals are sold, the fixed costs can be widely spread among cows, reducing costs per head. The number of calves as a percentage of exposed cows determines the calf crop. Calf crop together with weaning weights are used in the determination of available total beef weight for sale (Jones and Simms 1997). Investment in productive cows is vital in a cow-calf operation as these are the units that generate revenue. However, there is no major justification for heavy investment in infrastructure in a cow-calf enterprise. For profitability in a cow-calf enterprise, the ability to control costs is a vital skill. Broadworth et al. (1993) emphasized this argument considering that there are narrow margins for profits in a cow-calf enterprise.

Rangeland models and decision support systems

Many models have been developed to aid in the management of rangelands. Such models Include GRASP (Littleboy and McKeon 1997), CENTURY (Parton et al. 1992), PHYGROW (Center for Natural Resources Information Technology 2005), and SPUR (Wight 1983) among others.

Most of these models are complex and required extensive data for calibration and use rendering them unfriendly for use by ranchers. They are, however, useful tools for rangeland systems research and a lot of work has gone into their development.

GRASP is a pasture growth model developed for Australian rangelands. It combines a soil water model with above-ground dry-matter flow to predict grass growth.

It simulates growth on a daily time step. To parameterize the model requires extensive soil moisture data, precipitation characteristics and detailed production data such as soil nutrient status and plant nutrient status. GRASP can be used in assessment of drought risks, simulating grazing options, assessment of safe carrying capacity and evaluation of impacts of climate change and CO_2 increases. The model is site specific and cannot be easily used for other sites.

CENTURY is a more general, long-term plant-soil-nutrient model. It is used to enhance understanding of grasslands and agroecosystem dynamics. The model is used in the analysis of soil organic matter dynamics in response to changes in management and climate. The model relies heavily on the vegetation types and CO_2 levels in the system. Impacts of grazing and fire on plant production can be evaluated using CENTURY, but it has no livestock component.

PHYGROW is a hydrologic based plant growth simulation model intended to simulated forage production for a site (Center for Natural Resources Information Technology 2005). It is site specific and has to be re-parameterized for each site. It is intended to be a general ecosystem model with limited livestock and economic functions.

SPUR is a process level simulation model designated to determine and analyze management scenarios as they affect rangeland sustainability and to forecast the effects of climate change on rangelands. It is a multipoint model designed to allow for direct competition among the various vegetation species. SPUR incorporates the impacts of both wildlife and livestock on rangelands. The model was developed to allow for management practices to be incorporated, thus serving as a decision-making tool. However, it requires inputs daily climate data It is difficult to parameterize and is not used by ranch managers.

A number of decision support systems have been developed to aid grazing managers at local level. These include GRAZPLAN (Moore et al. 1997), The Grzing Manager (TGM), (Kothmann and Hinnant 1994, 1999) and GLA (Stuth et al. 1990).

GRAZPLAN is a suite of models developed for temperate Australian grazing lands. The pasture model (Moore et al. 1997) distinguishes multi-species growing together keeping track of tissue pools within each species. The nutrient economy of plants is models using a demand supply approach. The extensive data required to initialize the decision system, preclude its use by most ranch manageers

GLA was developed to assist researchers and policy analysts to assess economic and environmental impacts of various grazing land management strategies. It is not a simulation model. GLA contains components such as expert systems, dynamic programming, integer programming, linear programming, mixed integer programming and multi-object programming (Stuth et al. 1990). GLA allows users to characterize land size, land-use, soil and plant community growth profile, and long-term management response of management units. The level of knowledge required to use the model is high, however the output can be useful to managers.

TGM monitors forage supply and demand at the whole ranch, grazing systems and pasture or allotment basis. The integration of livestock management and grazing enterprise in TGM provides a verifiable method of obtaining and consolidating livestock and resource information for timely grazing management decisions (Pittroff et al. 2005). TGM use small number of aggregated variables. The simplicity of TGM makes it an attractive tool for use at local ranch level. The rancher selects desired intensity of grazing for each pasture and develops a grazing plan and scheduled for any burning or hay harvesting. Both forage production and animal demand are measured as demand days, where one demand day is 15 Mcal of net energy for maintenance or gain. TGM is not a utilization model because grazing demand is not calculated based on consumed biomass (Pittroff et al. 2005)

CHAPTER III

MODEL DESCRIPTION

Study site

Livestock production data for this research were obtained from research conducted by the Texas A&M University Research and Extension Center at Vernon. This center, established in 1971 and opened in September 1972, was designed to provide support for agricultural enterprises of the Rolling Plains region of Texas. The Rolling Plains of Texas extends eastwards from the High Plains escarpment to the Western Cross Timbers, and south to the Edwards Plateau covering about 9.7 million hectares (Texas Parks and Wildlife 2003). The climate of the Rolling Plains varies from semiarid continental in the west to sub-humid temperate in the east. The region receives from 500 to 720 mm of rainfall annually mainly in summer thunderstorms (Figure 3). Summer temperatures are hot (mean max. 38°C) while winters are generally mild except for brief periods when cold fronts push arctic air masses into the region. Warm temperatures and brisk, dry winds promote a high evaporation rate and lessen the effectiveness of precipitation.

The geology of the Rolling Plains region is varied with sandstone, mudstone, shale, and limestone outcrops found at various locations, giving rise to soils that have low infiltration rates but are moderately fertile. Caliche and gypsum strata are common due to the relatively small amounts of rainfall. The region, which is dominated by grasses 0.3 to 1 m tall, lies at the southeastern edge of the Great Plains physiographic province that extends northward as the mixed prairie through the mid-continental United States to Canada (Texas Parks and Wildlife 2003).

The topography and vegetation of the Rolling Plains are diverse. Terrain and plant communities vary from relatively flat midgrass areas of sideoats grama (*Boutelona curtipendula* (Michx.) Torr) to rough broken slopes supporting redberry juniper (*Juniperus pinchotti* Sudw.) or shinoak (*Quercus mohriana* Walt.). Gently rolling hills support little bluestem (*Schizachyrium scoparium* (Michx.) Nash var *scoparium*) and sideoats grama species on shallow soils. The major drainages and floodplains of the Red, Brazos, and Colorado rivers that transverse the area may support a mixture of tall and midgrasses within a deciduous hardwood corridor. On many sites, the presence of sideoats grama and/or little bluestem best characterizes the mixed prairie of the Rolling Plains. Other plants that are widespread throughout the region include: mesquite (*Prosopis glandulosa* Torr.), lotebush (*Ziziphus obtusifolia* (T. &G.) Gray), prickly pear (*Opuntia lindheimeri* Engelm var *lindheimeri*), blue grama (*Boutelona gracilis* (H.B.K.) Lag ex Griffiths), Texas wintergrass (*Stipa leucotricha* Trin. &Rupr.), silver bluestem (*Bothriochloa laguroides* (DC) Herter subsp. *torreyana* (Steud) Allred & Gould *Bothriochloa sacchariodes* (SW) Rydb.), vine-mesquite grass (*Panicum obtusum* H.B.K), and California cottontop (*Digitaria californica* (Benth.) Henr.). A large and diverse component of forbs and legumes as well as other grasses and woody plants are often found in association with the dominant grasses.

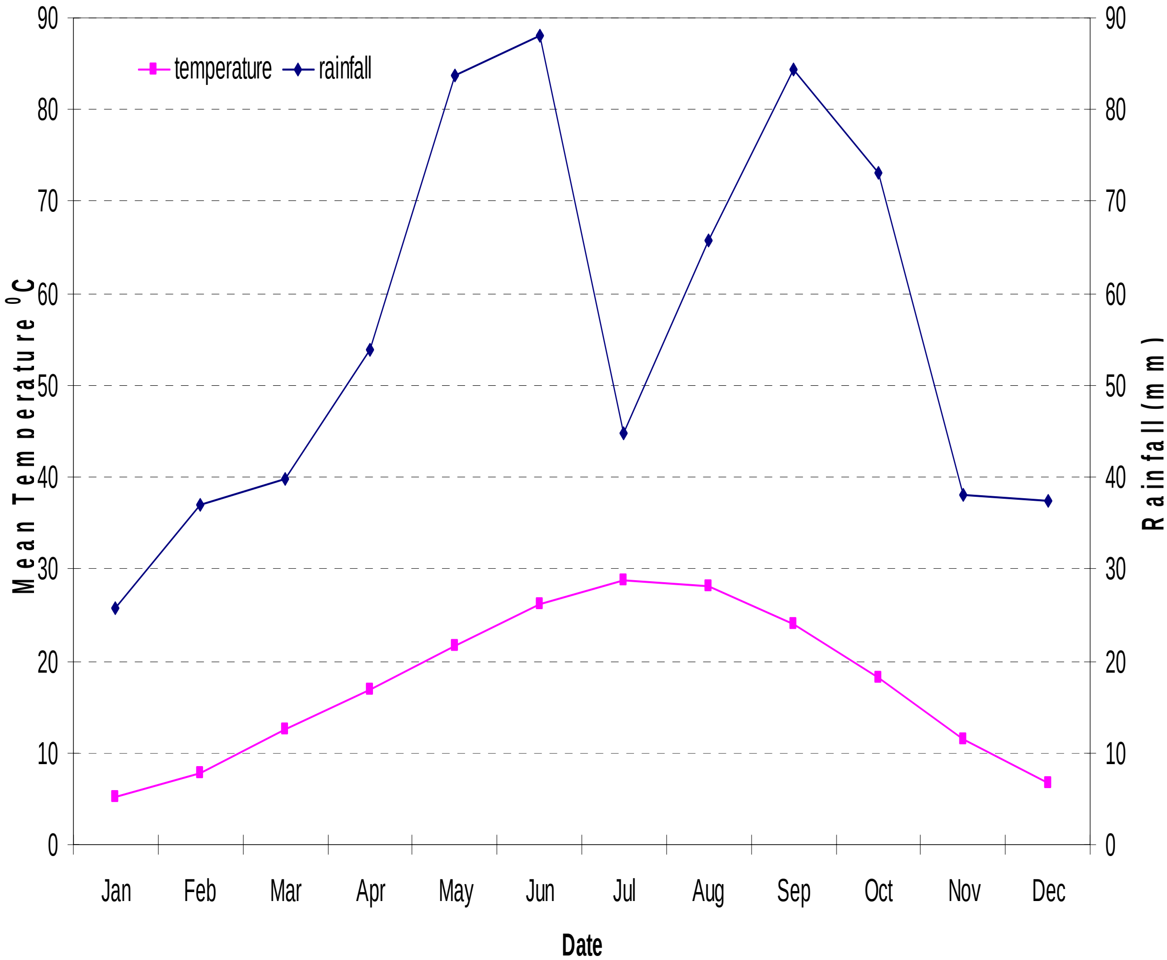

Figure 3. Long-term (75-years data), average monthly precipitation and mean monthly temperatures for Throckmorton.

Climatic factors, intense seasonal grazing, and periodic wildfires were major influences in the development of the Rolling Plains vegetation. During the 1870s, bison were eliminated as settlement of the Rolling Plains began. Many of the more favorable Mixed Prairie sites with deep productive soils and reasonably level terrain were broken out for cropland. Those sites not suitable for farming were left in native vegetation and used as range for domestic livestock, mainly cow-calf on native range (Texas Parks and Wildlife 2003).

Texas is divided into 12 cooperative extension districts (Figure 4). Each district is manned by agricultural economists who evaluate the economic viability and trends in the agricultural sector on a continuous basis. The Rolling Plains constitutes district 3 (Texas Cooperative Extension 2004). Economic data used in this project were extracted from the data published in the Extension Agricultural Economics website (http://jenann.tamu.edu/district/rollingplains)

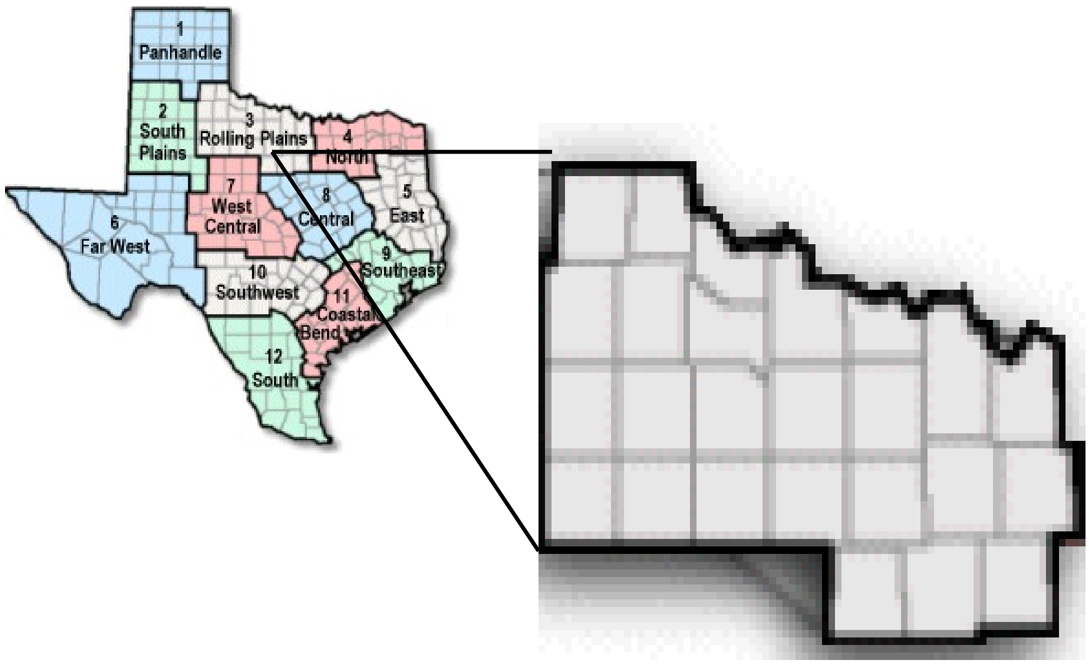

Figure 4. Map of Texas showing the Rolling Plains extension districts of Texas (source: Texas Agricultural Extension Service 2004).

Model description

A stochastic, compartmental model for adaptive livestock management (MALM) was developed from SESS (Diaz-Solis et al. 2003) using difference equations programmed in STELLA® 7.0 (High Performance Systems Inc., Hanover, New Hampshire). The model had three distinct compartments (Figure 5), climate, forage production and animal production

Precipitation is the major driving variable in the model. Climate drives forage production which consequently drives animal production. Animal production also affects forage production because the numbers of animals affect utilization levels (grazing pressure).

Like SESS (Diaz-Solis et al. 2003) MALM simulates the dynamics of forage classes, range condition, diet selection and animal production using difference equations. The concept of rain use efficiency (RUE) proposed by Le Houreou (1984) is used to related aboveground net primary production and precipitation. Change in range condition is simulated as a function of proportion of annual net primary production, a measure of grazing intensity. There are two main categories of management strategies, fixed and flexible stocking strategies. Unlike SESS, MALM, was developed to allow a user to choose a stocking rate and maintain stocking rate constant or to set criteria for managing a flexible stocking rate. The model is developed to allow for any number of stocking rates to be evaluated as desired by the user. Two fixed stocking rates are discussed in the model evaluation chapter namely, light (0.1 $AUM \cdot ha^{-1}$) and heavy (0.2 $AUM \cdot ha^{-1}$). Five fixed strategies were evaluated in the model-use chapter, namely ultra-light (0.025 AUM·ha^{-1}), very light (0.05 AUM·ha^{-1}), light-moderate (0.13 AUM·ha^{-1}), moderate (0.17 AUM·ha^{-1}) and very heavy (0.25 AUM·ha^{-1}). Only a 40% utilization level was evaluated in the model evaluation chapter. Flexible stocking strategies evaluated in the model-use chapter include forage utilization levels of 5%, 10%, 20%, 30%, 40%, 50% and 60%.

Precipitation

SESS (Diaz-Solis et al. 2003) simulates forage production as a function of annual precipitation for a dominantly warm-season grass environment with one primary growth period each year. SESS uses annual precipitation to predict annual forage production, which is then partitioned into monthly production using constant proportions for each month (Diaz et al. 2003). Use of constant monthly proportions to partition precipitation removed seasonal variability of rainfall observed in natural systems.

In the Rolling Plains of Texas there are both warm-season and cool-season forage species. Monthly precipitation was randomly generated from a cumulative frequency distribution for each month (Grant et al. 1997). This was done to simulate observed seasonal variation in forage production, which is an important characteristic in stocking rate decisions. Sampling precipitation from a normal distribution using monthly means and standard deviations failed to adequately account for the observed monthly variability. It ignores the fact that there are months in some years that receive zero precipitation. For each month precipitation was generated using the equation

Equation 1

$$MPPT = RANDOM \ (cumulative \ frequency)$$, where MPPT = monthly precipitation

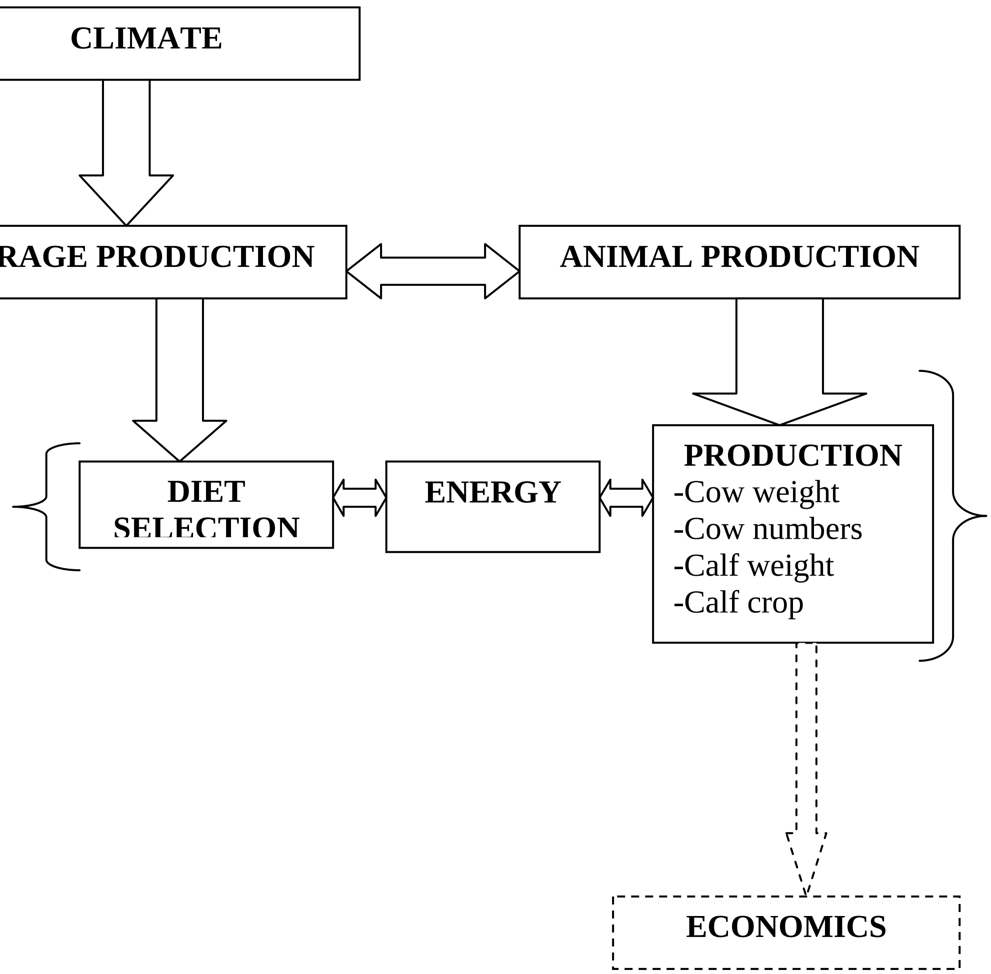

Figure 5. Schematic representation of MALM.

Forage production

Forage production was simulated on a monthly time step using a multiplicative function of range condition, rain-use-efficiency, and monthly precipitation (generated randomly or input as actual data) and a temperature index (the temperature index consists of monthly constants). The temperature index reduces growth during periods of low temperature. Based on the work of Diaz Solis et al. (2003), Sims and Singh (1978a, b), Lauenroth et al (1986) and Sala et al (1988) green standing crop (GSC) was calculated as

Equation 2

$GSC(t) = GSC(t - dt) + (Ginput - FSG - GC - GSCSin - GT) * dt$, standing crop (kg $DM \cdot ha^{-1}$)

where:

Equation 3

$FSG = F * (GSC - GC - GT)$, is the grass that senesces as a result of frost,

Equation 4

$Ginput = MNPP = RC * MPPT * Temperature\,GI * RUE$, monthly forage growth,

Equation 5

$GC = WRI * GFD * SR(AU/HA) * 30\ days/month$, is the forage that is consumed by cattle, where WRI is intake rate, GFD is the proportion of green forage in the diet,

SR (AU/HA) is stocking rate.

Equation 6

$GSCSin = GSC * SR$, is the forage that senesces as a consequence of aging,

Equation 7

$GT = SR\ (AU/HA) * TRA * 30 * (GA/100)$, is the forage that is lost due to trampling.

An annual RUE (Rain-use-efficiency, kg green forage·mm^{-1} of precipitation) = 6.0 + SC was used assuming that use of monthly precipitation and the monthly temperature growth index (Table 1) partitions RUE, correcting for monthly fluctuations. SC is a measure of soil capacity for water infiltration and retention. SC is assigned value of 1 for high, 0 for medium and -1 for low capacity.

Table 1. Temperature growth index

Month	Temperature growth index
January	0.1
February	0.5
March	0.7
April	1.0
May	1.0
June	1.0
July	1.0
August	1.0
September	1.0
October	1.0
November	0.7
December	0.5

Senescence

Senescence and Age equations from the work of Blackburn and Kothmann (1989) were adjusted from daily to monthly and used in the model.

Equation 8

$$\text{SENESCENCE}(t) = \text{SENESCENCE}(t - dt) + (\text{GSCSin} - \text{GSCSout}) * dt$$

dt = one month

The rate of senescence is estimated as a linear function of basal relative turnover rate and per-unit change in age of green standing crop, senescence-aging (SA), as described in Blackburn and Kothmann (1989) multiplied by 30.4 to convert to a monthly time step. It is noted that this is a simplistic conversion of the rate from a daily time step to a monthly time step; the results indicate the conversion is sound.

Equation 9

$$SA = 0.018 * 30.4 + 0.000075 * 30.4 * AGE$$

where

Equation 10

$$AGE(t) = AGE(t - dt) + (AGEIN - AGEOUT) * dt$$

AGE is in months

Equation 11

$$AGEIN = \text{If } GSC = 0 \text{ then } AGE = 0 \text{ else Min } (((GSC - Ginput)/ (GSC)) * AGEP + 1, 3)$$

Equation 12

$$AGEOUT = \text{If } AGE > 3 \text{ then } AGE \text{ else } 0$$

Age of the green parts of grass is allowed to accumulate up to 90 days after which all the material senesces and when GSC is zero there is no senescence.

The movement of material from the green pool to the dead standing pool (DSC) as described in Diaz-Solis et al. (2003) was not altered.

Dead standing crop

The movement of the dead standing crop (DSC) was modified from SESS (Diaz-Solis et al. 2003) to include the effects of temperature and precipitation in the process. The equation was simplified to focus mainly on the disappearance of leaf material as this is the plant component that often experiences large variation in month-to-month disappearance rates. The equation for the conveyance of DSC to litter is as follows

Equation 13

$$DL = DEADIS * (DSC - DC - DFT) \ \text{kg DMha}^{-1}.\text{mo}^{-1}$$

where: DL is the movement of DSC to litter, DEADIS is rate of movement of dead material as a result of average monthly temperature (AMT, ^{0}C) and monthly precipitation (MPPT, mm)

Equation 14

$$DEADIS = 1 - EXP(-0.003077 * MPPT) + 0.0005 * AMT$$

Animal production

Stocking rate decisions

Most livestock enterprise management decisions are made annually taking into account forage production and market factors. Decision points are times within a management year at which forage inventories are conducted to estimate available and potential forage production and make stocking adjustments. MALM incorporated three decision points within an operation's calendar at which forage SC were evaluated for flexible stocking strategies.

Late June or early July: On average, 60-70% of the forage production occurs by this time (M.M. Kothmann personal communication, 2003, Texas A&M University, College Station). Forage availability is inventoried, decisions to reduce stocking rate either by culling or selling are made. Assessment of market prices is made on or just before this period.

September-October: potential winter forage availability is assessed at this time as a criterion for decisions to alter stock numbers. Typical decisions during this time include weaning date, culling rate and replacement rate and stocking rate.

Late March or early April: Stocking rate adjustments can be made based on levels of forage-use, previous year's forage production and the potential for a good or bad growing season. Decisions may include sale of open cows and culling to reduce cow numbers.

Stocking rate model parameters

Light, "safe" stocking rate for the Rolling Plains of Texas, with annual long-term average precipitation of about 600 mm, was 0.1 $AUM \cdot ha^{-1}$. This light stocking rate equates to consumption of about 20% of annual average net primary production (ANPP). This stocking rate is an auxiliary variable in the model which remains constant throughout a simulation, independent of forage supply.

The heavy fixed stocking rate was set at 0.2 $AUM \cdot ha^{-1}$. This was maintained in the model throughout a simulation and was independent of level of forage production.

The stocking rate is representative of stocking rate in the study area (Kothmann et al. 1970, Knight et al. 1990).

Flexible stocking rates were based on the availability of forage. Light stocking was used when forage fell below a threshold 300 kg·ha^{-1} during a decision point, June or October. O'Reagain et al. (2003), suggest that for practical and economic reasons it is often not feasible for management to reduce animal numbers by more than 30 % unless management is design to specifically do so regardless of economic implications. If forage was above the threshold, stocking rate was calculated as:

Equation 15

$$SR\ (AUM.ha^{-1}) = HARV\% * (TSCR - SR\_threshold)/(m * 340)$$

where: HARV is the proportion of forage utilized whose values are 5, 10, 20, 30, 40 and 50 representing ultra-light, very light, light, moderate, heavy and very heavy utilization respectively. TSCR is total standing crop (kg·ha^{-1}), SR_threshold is 300 kg·ha^{-1}, m is the number of months between decision point (five months for a June decision and seven months for an October decision) and 340 kg is the monthly forage demand for each cow.

The assumption is that restocking will often occur at a lower rate than destocking as ranchers become more cautious after experiencing high animal losses as a result of previous droughts, also the market price of heifers can be limiting. Flexible stocking strategy at 40% utilization level was evaluated in the study together with light and heavy fixed stocking strategies. The decision for the stocking rate management strategy was formulated mathematically using the following logical statement:

Equation 16

If(SRmgmt=0) then SR_light_fixed else if (SRmgmt=2) then SR_heavy_fixed else if(SRmgmt=3) then SR_light_moderated_fixed else if(SRmgmt=4) then SR_moderate_fixed else if(SRmgmt=5) then SR_very_heavy_fixed else if(SRmgmt=6) then VVLight else if(SRmgmt=7) then Vlight else if(SRmgmt=1) and (M=6) and (TSCR<SR_threshold) then SR_light_fixed else if (SRmgmt=1) and (M=10) and (TSCR<SR_threshold) then SR_light_fixed else if(SRmgmt=1) and (M=6) and (TSCR>SR_threshold) then HARV%*(TSCR-SR_threshold)/(5*340) else if (SRmgmt=1) and (M=10) and (TSCR>SR_threshold) then HARV%*(TSCR-SR_threshold)/(7*340) else SR_AUM_HA_last_month

where: SR_AUM_HA is animal units per hectare, SRmgmt is an index representing the management of stocking rate where SRmgmt=0 is the decision to use the light fixed stocking rate (0.1 AUM·ha^{-1}), SRmgmt=1 is the decision to use flexible stocking rate, SRmgmt=2 is the decision to use fixed stocking rate (0.2 AUM·ha^{-1}), SRmgmt=3 is the decision to use fixed stocking (0.13 AUM·ha^{-1}),

SRmgmt= 4 is the decision to use fixed stocking (0.17 AUM·ha^{-1}),

SRmgmt=5 is the decision to use fixed (0.25 AUM·ha^{-1})

SRmgmt=6 is the decision to use fixed stocking (0.025 AUM·ha^{-1})

SRmgmt=7 is the decision to use stocking (0.05 AUM·ha^{-1})

SR_threshold = 300 kg·ha^{-1} is the TSCR threshold used to make restocking and destocking decisions.

To maintain a shortgrass prairie in good condition a threshold of 336 $kg \cdot ha^{-1}$ is required while for the midgrass prairie 840 $kg \cdot ha^{-1}$ is required (Lyons and Machen 2004). For the model there was no separation of the grasses, therefore, the 300 $kg \cdot ha^{-1}$ threshold was used.

SR_AU_HA_last_month is the stocking rate prior to decision point. The stocking rate management decisions are auxiliary variables that can be changed to simulate the manager's desired values.

The following parameters were simulated: animal weights, weaning weights, BCS, and range condition. The key production output variables of the model are listed in Table 2.

Table 2. Main model output variables

Variable	Units
Number of cull cows	#
Weight of cull cows	kg
Number of replacement heifers	#
Weight of replacement heifers	kg
Calf crop	#
Calf weaning weight	kg
Range condition	unitless
BCS	unitless

Body condition score and cow weight

Change in BCS of an animal depends on previous BCS, and is an indication of plane of nutrition. In the model, BCS was calculated as follows

Equation 17

BCS = If D1NTCOWS>0 and COWIN=0 then BCS else If COWIN=0 and D1NTCOWS=0 then 0 else If DMCALM>0 then DMCALM/IBC else 0

where, BCS is BCS for cows; DMCALM is energy for maintenance, IBC is conversion of weight to BCS, COWIN is current number of cows and DINTCOWS is number of cows previous month

BCS of an animal is a measure of the fat and muscle content in the animal and there is a strong link between BCS and animal weight.

In the model shrunk cow weight was calculated as a function of body condition as follows:

Equation 18

$$SBW = MWBC5 * PW$$

where, SBW is shrunk body weight, MWBC5 is initial cow weight = 450 kg, PW is a function that calculates weight based on proportion of initial weight at each BCS (Table 3).

Table 3. The relationship between BCS and SWB at BCS 5

Body Condition Score	Proportion of initial weight or average weight
1	0.765
2	0.813
3	0.867
4	0.929
5	1.000
6	1.080
7	1.180
8	1.300
9	1.440

Pregnancy and calf crop

Reproduction is vital in a cow-calf enterprise. Cows need adequate nutrition to promptly cycle to ensure early conception in the breeding period, providing for fetus and calf. The condition of the animal is critical in reproduction and body condition scoring is used in estimating the conception rates and potential calf crop. Cows of BCS less than 4 require 12 more days to first estrus compared to cows of BCS of 5 or greater (Hoppe 1997). In the model, the relationship in Table 4 between BCS and Pregnancy was used to estimate pregnancy in cows.

All cows that were open or died were replaced in October of each year. Cow mortality was determined based on the BCS as shown in Table 5. A constant rate of 0.0005% per month of calf mortality was assumed in the model.

Table 4. The relationship between BCS and annual cow pregnancy rate

Body Condition Score	**Pregnancy Rate**
1	0. 00
2	0.30
3	0.60
4	0.80
5	0.95
6	0.95
7	0.95
8	0.95
9	0.92

Table 5. The relationship between BCS and monthly rate of cow mortality

Body Condition Score	Mortality Rate
1	0.050
2	0.040
3	0.007
4	0.002
5	0.001
6	0.001
7	0.001
8	0.001
9	0.001

Calf weaning weight

Calf weight was calculated as a function of energy intake of the cow. Cow energy for intake was considered to be an indicator of nutrient status. The higher the intake the higher the potential for milk yield and the higher the nutrient intake of the calf from grazed forage. High milk yields available to calves often translate to high weight gain.

Measured calf weight data and simulated energy intake, (megacalories per kg of dry matter, $Mcal \cdot kg^{-1}$ DM), under heavy and light stocking rate were used in a regression to determine the upper and lower limits of the relationship between energy and calf weight. Minimum weight was 160 kg·head^{-1} at 5.00 Mcal·kg^{-1} DM and the maximum was 250 kg·head^{-1} at 17.00 Mcal·kg^{-1} DM Weaning weights were estimated under different stocking strategies using this relationship between energy intake and calf weights. The simulations were run for a period of 20 years on a monthly basis

Because all calves were sold at weaning, no replacement heifers were kept, the calves were not separated into steers and heifers for the purposes of economic analysis. The weighted price of heifers and steers was used in the economic analysis.

Range condition

Diaz-Solis et al. (2003) details the simulation of changes in range condition. Range condition is modeled based on the proportion of ANNP consumed by livestock. An initial range condition is set by the user and, based on stocking rate, soil condition, and annual precipitation of the range the condition will decrease or increase from the initial condition. This approach for simulating range condition emphasizes the site potential rather than the departure from climax vegetation, an ecological approach (Smith 1979). In the development of the range condition classes, recognition is made of the impact of previous management strategy on how the range responds. No changes were made when MALM was developed on the structure of the range condition submodel as earlier developed by Diaz-Solis et al. (2003).

Economic analysis

Economic parameters were calculated external to the model using livestock production output data from the model. Net income calculations were performed on "per animal" variable returns and costs. The simulations assumed same area for all the strategies. It was, therefore, assumed that fixed costs ha^{-1} were relatively similar for all stocking rate strategies. Such costs include labor, hired management, machinery and equipment and related running costs and land costs. Only economic parameters affected by number of animals were evaluated. These included replacement and lease grazing costs

Projected costs and returns for cow-calf production from the Rolling Plains were used in the economic analysis (Texas Agricultural Extension Service 2004). In order to account for variation in prices from year to year, median, minimum and maximum projected costs for the years 1999 to 2003, for each livestock category, were used to estimate net income for the future 5 years (Table 6). Sensitivity analysis, with arbitrary percentage decrease or increase in prices, was considered too subjective for use. The generation of random prices based on the historic distribution of prices was also rejected on the basis that it would mask the simple objective of demonstrating the variation in profitability due to stocking strategy. Lease grazing was assumed as opposed to ownership of the ranch and a cost of $110.00 per cow year was assumed (W.E. Pinchak, Ruminant Nutritionist and land owner, TAES, Texas A&M Univ. Vernon). Also evaluated was economic returns based on lease grazing cost per unit area with a cost of $14.00 ha^{-1} assumed.

The model simulated February calving and September weaning. Open cows were culled at weaning. All calves were sold at weaning. The cow replacement strategy chosen for this study was to purchase pregnant replacement heifers weighing about 380 kg. Purchase of the replacement heifers was the major variable cost affecting the replacement rates for different stocking strategies.

Gross income was calculated as:

Equation 19

$$GI = \sum (CALV07out * weaningweight * averagecalfprice, sellopen * SBW * cullcowprice)$$

where, CALV07out is the number of weaned calves; sellopen is the number of cull cows and SBW is the shrunk cow weight

Gross cost of replacement heifers was calculated as:

Equation 20

$GC = BUY * 385.9kg * bredheiferpurchaseprice + cows * 110.00$ **,** where BUY is the number of replacement heifers, cows is the number of cows; and 385.9 kg is the average weight of replacement heifer.

Economic analysis was performed three times using the median, minimum and maximum prices for each production category as described above, respectively. Table 7 shows the categories and formulas used in the calculation of net income.

Table 6. Gross prices used in the economic analysis of a cow-calf enterprise (Texas Agricultural Extension Service 2004)

Production Description	1999	2000	2001	2002	2003	Median	Min	Max
Cull cows ($\$\cdot kg^{-1}$)	0.85	0.77	0.97	0.84	0.84	0.84	0.77	0.97
Average calf price ($\$\cdot kg^{-1}$)	1.84	1.84	2.31	2.05	2.05	2.05	1.82	2.31
Replacement bred heifer price ($\$\cdot kg^{-1}$)	2.42	2.73	3.17	2.91		2.82	2.42	3.17
Lease grazing ($\$\cdot cow^{-1}$)	110.00	110.00	110.00	110.00	110.00	110.00	110.00	110.00

Table 7. Calculation of net income for each stocking strategy

Production Description	Return	Cost	Net Income
Cull Cows ($\$\cdot kg^{-1}$)	number of cull cows*weight *price		
Calf price ($\$\cdot kg^{-1}$)	number of calves*weight *price		
	Gross Income		
Replacement bred heifer price* ($\$\cdot kg^{-1}$)		number of replacement heifers*weight *price	
Lease grazing ($)		number of cows*110.00 **OR** number of cows*14.00$\cdot ha^{-1}$	
		Gross Cost	
Net Income			**Gross Income-Gross Cost**

CHAPTER IV

MODEL EVALUATION

Methods and materials

Data sources

Forage production, animal, and precipitation data were obtained from the Texas Experimental Ranch near Throckmorton in the east central portion of the Rolling Plains. Primary production data for the period 1985 to 1988 were used to evaluate the model. Animal production data were evaluated for authenticity by reviewing published data for the area since the 1960s (Kothmann et al. 1970, Knight et al. 1990, Teague and Foy 2002). Precipitation data were obtained from National Climate Data Center, NCDC, (http://ncdc.nndc.noaa.gov) for the Throckmorton weather station.

Data analysis

One hundred simulations, each for 20 years, were conducted for each of the three stocking strategies. The experimental design was a 3 x 20 factorial. Means of measured and simulated data were compared using the independent samples t-test method. The t-test has an advantage when sample sizes are small as is the case with field data where data points can be as few as 6 samplings a year (Ott 1993).

Precipitation

To verify the model, simulated precipitation was compared to measured precipitation for the period January 1985 to December 1988. The model simulated precipitation adequately (Figure 6). The 4-year simulated mean monthly precipitation was 59.49 ± 52.47 mm and measured mean monthly precipitation was 59.64 ± 46.87 mm. There were no significant differences between the measured and simulated monthly precipitation means (df= 94, t=1.986, p=0.946). There was higher spread in the simulated precipitation compared to measured precipitation. For the winter months there was a general over-estimation of precipitation, but production was limited by temperature. There was general agreement between in seasonal patterns and total precipitation for simulated and measured precipitation data for Throckmorton, Texas (Figure 6). In the winter months the model generally underestimated precipitation.

Forage production

Green standing crop (GSC) is primarily a function of growth, which responds to precipitation and temperature. TSCR is significantly affected by stocking rate. A comparison of measured and simulated GSC indicated no significant differences (df= 44, t= 2.02, p=0.733). The model satisfactorily predicted forage growth (Figure 7). The slight shifts in the production peaks can be attributed to the monthly time step of the model and the sampling dates for field data, rather than failure by the model to accurately predict production. Field forage production data were measured in stocking rate trials at Throckmorton for the period 1985 to 1988. The data used are mainly from the light and moderate stocking rates. Comparison of the measured and simulated data for total standing crop (TSCR) indicated no significant differences between the measured TSCR and simulated TSCR for light stocking rate (df =58, t =2.00, p=0.434). The model, therefore, adequately predicted TSCR (Figure 8).

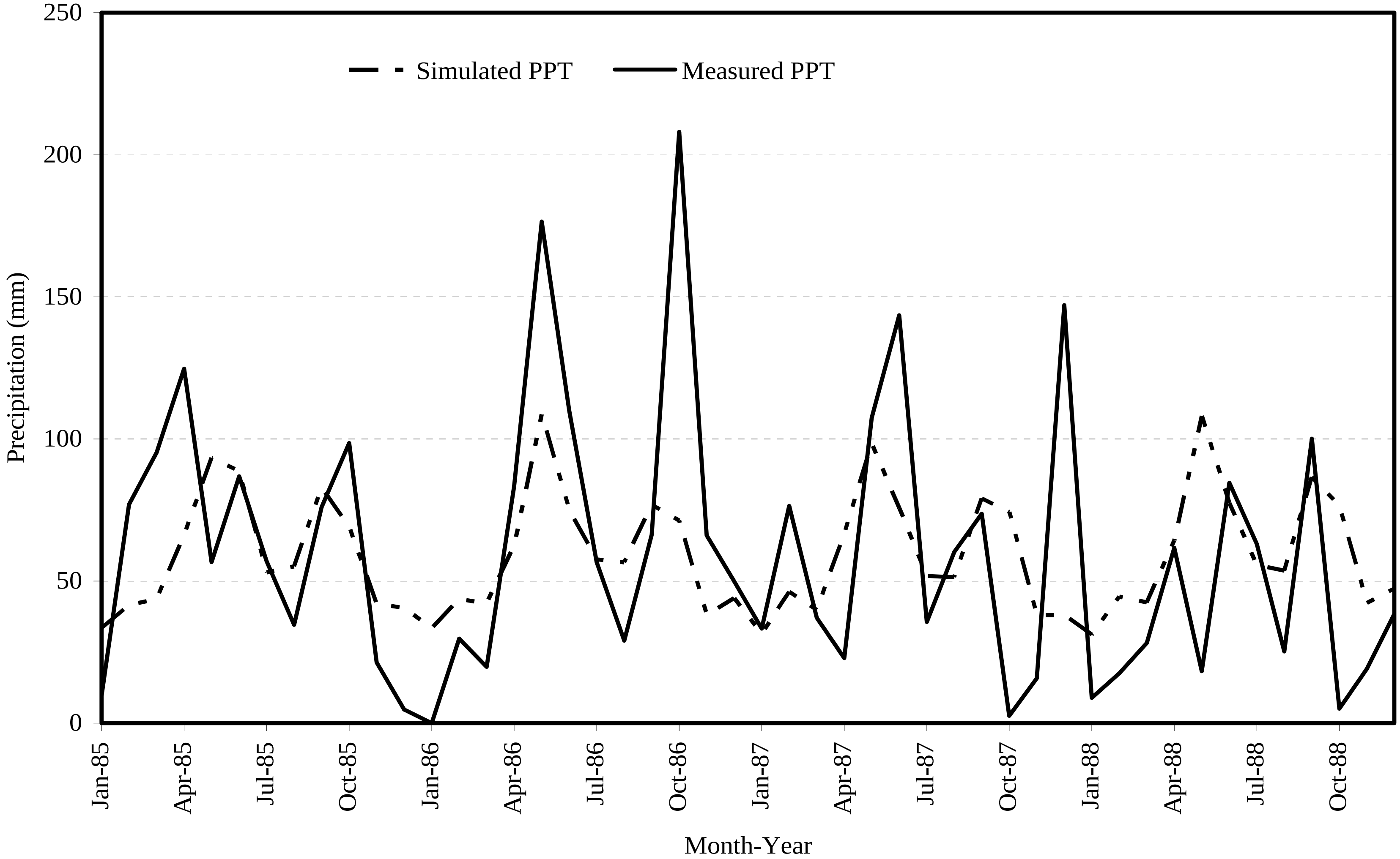

Figure 6. Evaluation of model prediction of monthly precipitation using the measured 1985 to 1988 precipitation from Throckmorton.

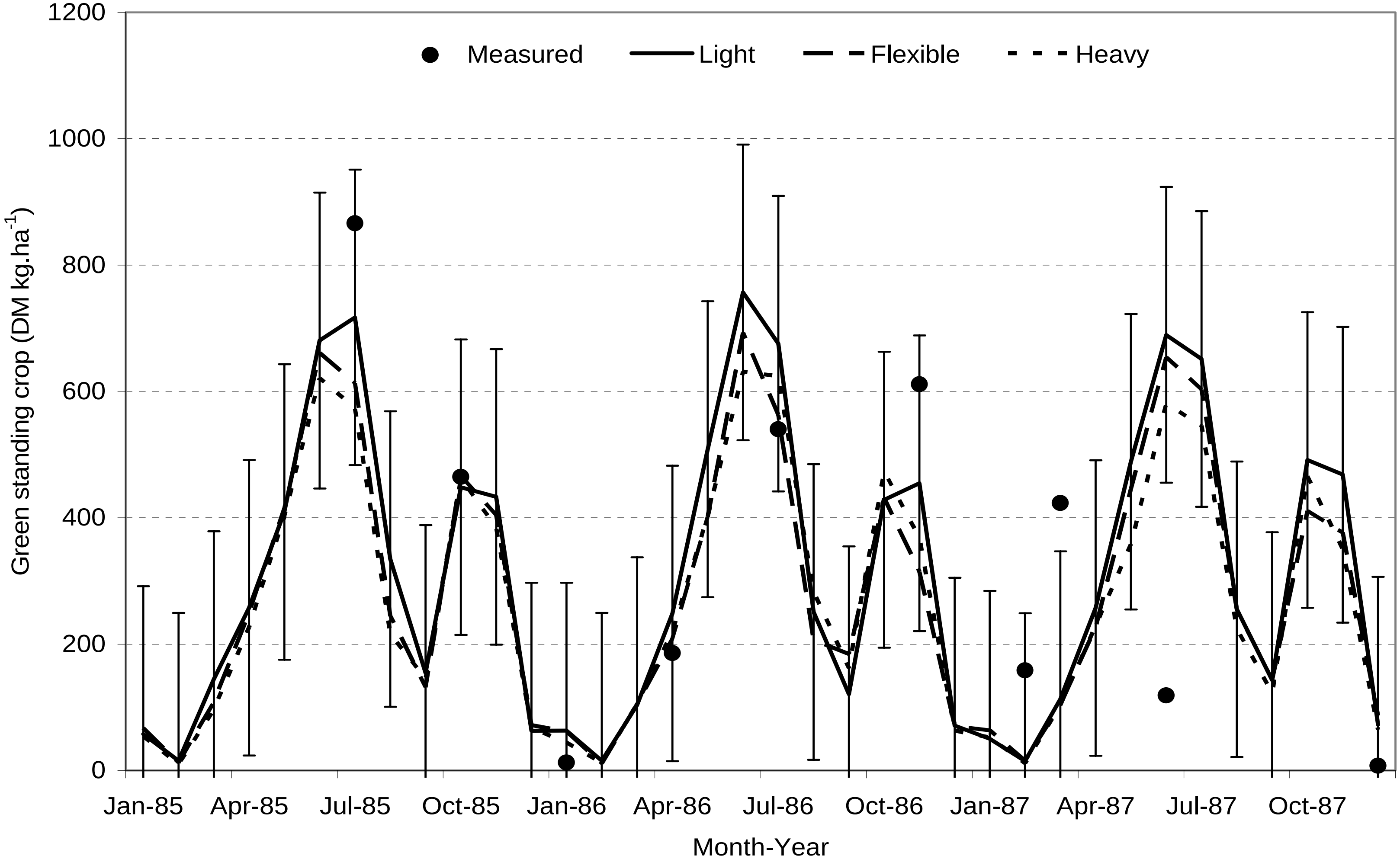

Figure 7. Comparison of measured standing crop (GSC) and simulated GSC for three simulated stocking strategies.

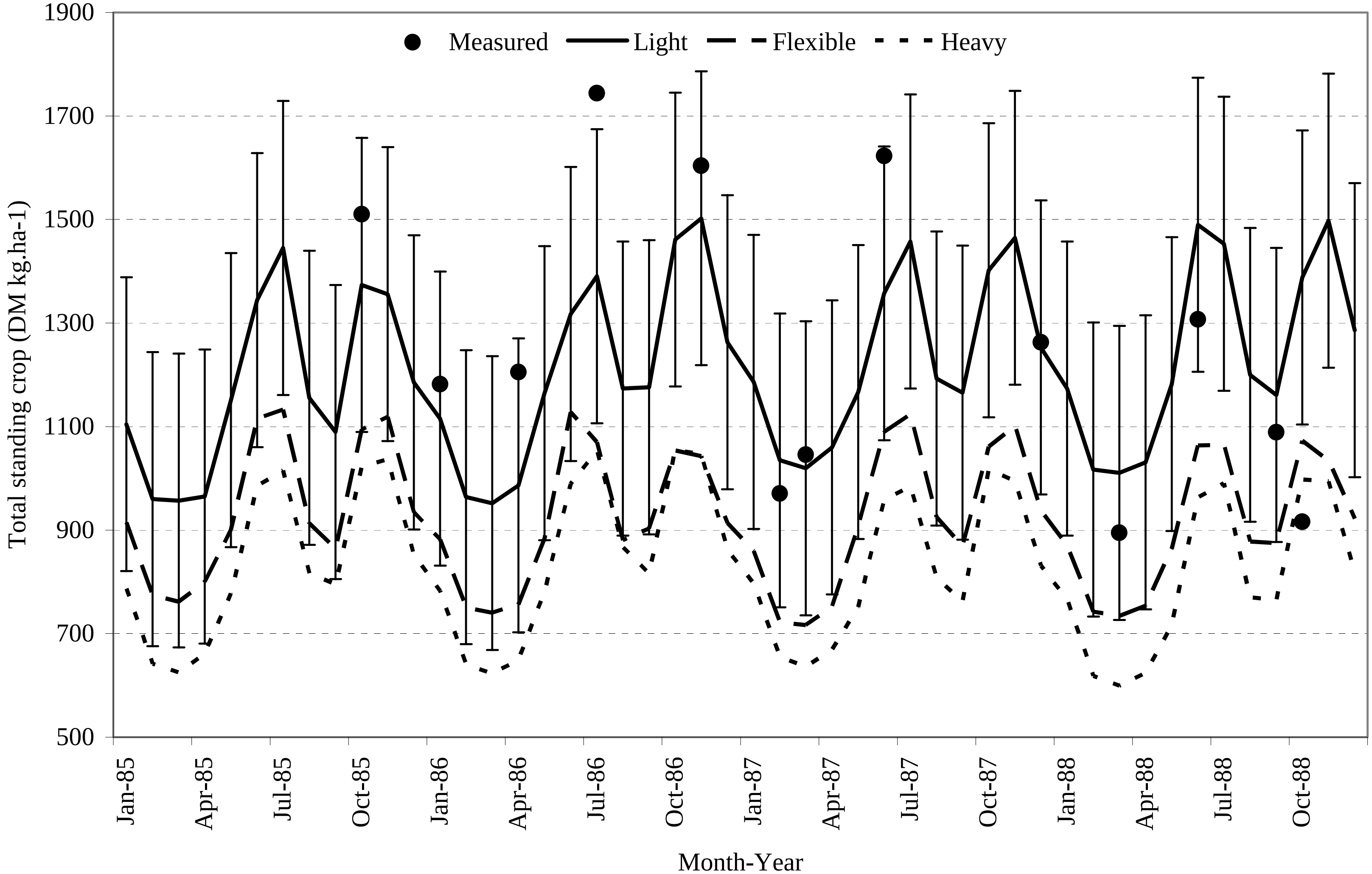

Figure 8. Comparison of measured total standing crop (TSC) and simulated TSC for three simulated stocking strategies.

Cow weights

Simulated shrunk body weights of cows at weaning did not differ significantly between measured and simulated light stocking strategy (df= 8, t=2.306, p=0.807) or between measured and simulated heavy stocking strategy (df= 8, t=2.306, p=0.374; (Figure 9). This is evidence that the model was adequately parameterized to predict animal weight. Variation in simulated shrunk body weight was lower than measured shrunk body weight under all evaluated stocking strategies. This can be attributed to greater number of replicates in the simulation than in the real systems. The model does not incorporate supplementation. In general, cows were lighter, at weaning, under heavy fixed stocking (410 kg) than under fixed light stocking (460 kg) and under flexible stocking at 40% forage utilization levels (450 kg).

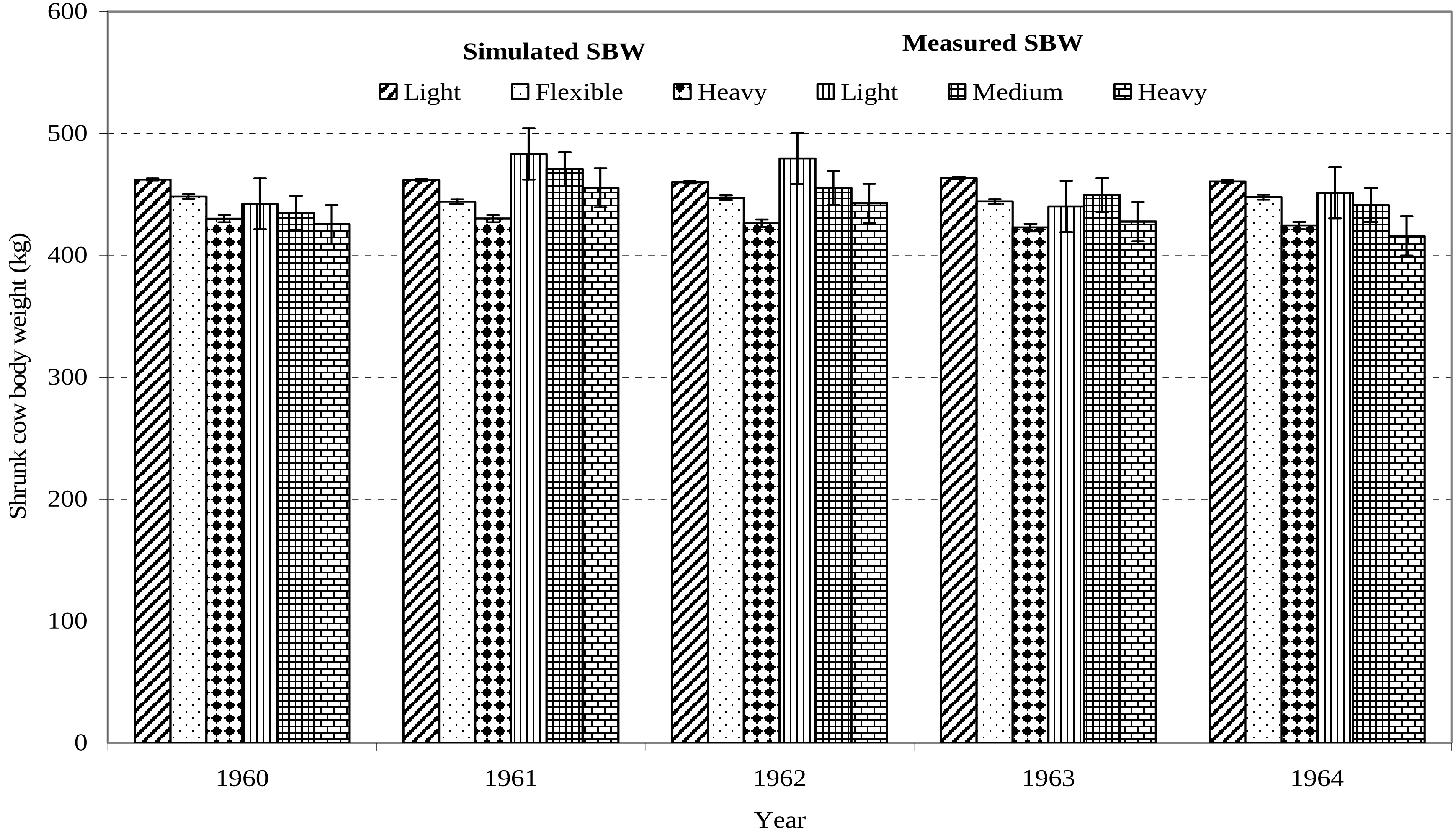

Figure 9. Comparison of measured and simulated shrunk cow weights for different stocking rates.

Calf weaning weight

The model was parameterized to wean and sell calves in September of each year. Weaning weights for the period 1963 to 1977 were used in model evaluation. It is important to note that measured heavy stocking rates were between 4.9 and 2.8 ha per animal unit year, which will be considered extremely heavy under no supplementation, as was the case in the model.

There were no significant differences in calf weight between simulated light stocking rate and measured light stocking rate (df=21, t=2.08, p=0.959). Also there were no significant differences between measured heavy and simulated heavy stocking rate (df=29, t=2.05, p=0.121). In general, the simulated and measured calf weights followed similar trends under similar stocking strategies (Figure 10). The low measured weaning weights for 1969 and 1976 are associated with the young cows that were brought into the experiments during these years (M.M. Kothmann, personal communication, College Station Texas). Furthermore, 1968 and 1969 were drought years resulting in reduced forage availability (Kothmann and Mathis 1974).

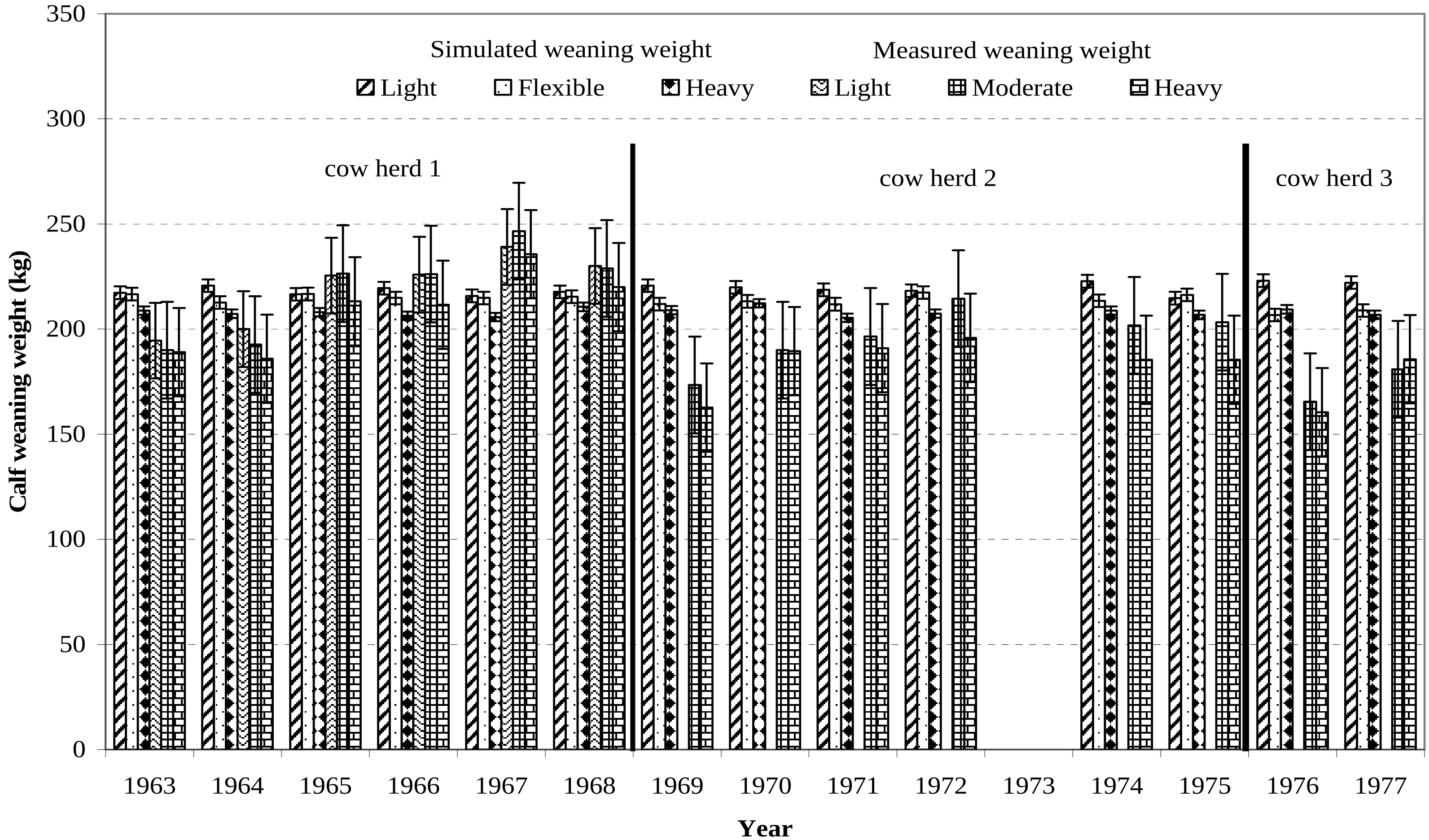

Figure 10. Comparison of measured and simulated calf weaning weights for different stocking rates. Solid bars between 1968 and 1969, and between 1975 and 1976 indicate points where the cow herd was replaced in the field trials.

The effects of stocking strategy on expected net income

The simulated flexible stocking strategy, on average, resulted in greater (\$19.62 ± 3.7) net incomes ha^{-1}, within each price category, compared to light (\$5.93 ± 0.99) or heavy stocking strategy (\$-17.35 ± 1.92, Table 8). Compared to the simulated light and simulated heavy stocking for the five years, simulated flexible stocking was more profitable, but enterprise net income was also most variable. Simulated heavy stocking resulted in lower net income compared to simulated light stocking rate. The low net income under heavy stocking can be attributed to a decrease in conception rate, a consequence of lower BCS. As a result of decreased pregnancy rate there is high replacement which is costly. Cull cows are sold at lower prices compared to the purchase price of replacement heifers. Also, calves under heavy stocking are weaned at low weights resulting in suppressed income when they are sold. Variation in net income for simulated light stocking rate was low throughout the 5 years (Figures 11, 12 and 13). The greatest variation in net income was observed under flexible strategy when the maximum price was used in the analysis (Figure 13). Overall, fixed heavy stocking resulted an average net loss of income of about \$17.35$\cdot ha^{-1}$. This can be attributed to depressed animal weights and high replacement rates.

Whitson et al. (1982) working in the Rolling Plains of Texas, reported high variability in net returns on heavier stocking. In their study, they did not evaluate light stocking rate, which may be why they did not find any difference among the various grazing systems and stocking rate treatments that were studied. It is also important to note that the year-to-year variation that was observed in their work was assumed to represent instability in income which justifies the need for the development of adaptive stocking strategies to cope with price and climate induced adjustment.

Table 8. Effects of price variation on net income ($\$\cdot ha^{-1}$) under different stocking strategies (means and standard deviations for 5-year simulation)

	Stocking rate strategy		
Price category	Light	Flexible	Heavy
Median	5.81 ± 0.15	18.08 ± 5.61	-19.21 ± 3.80
Maximum	6.97 ± 0.17	23.86 ± 6.30	-17.47 ± 4.25
Minimum	5.00 ± 0.13	16.91 ± 4.81	-15.37 ± 3.23

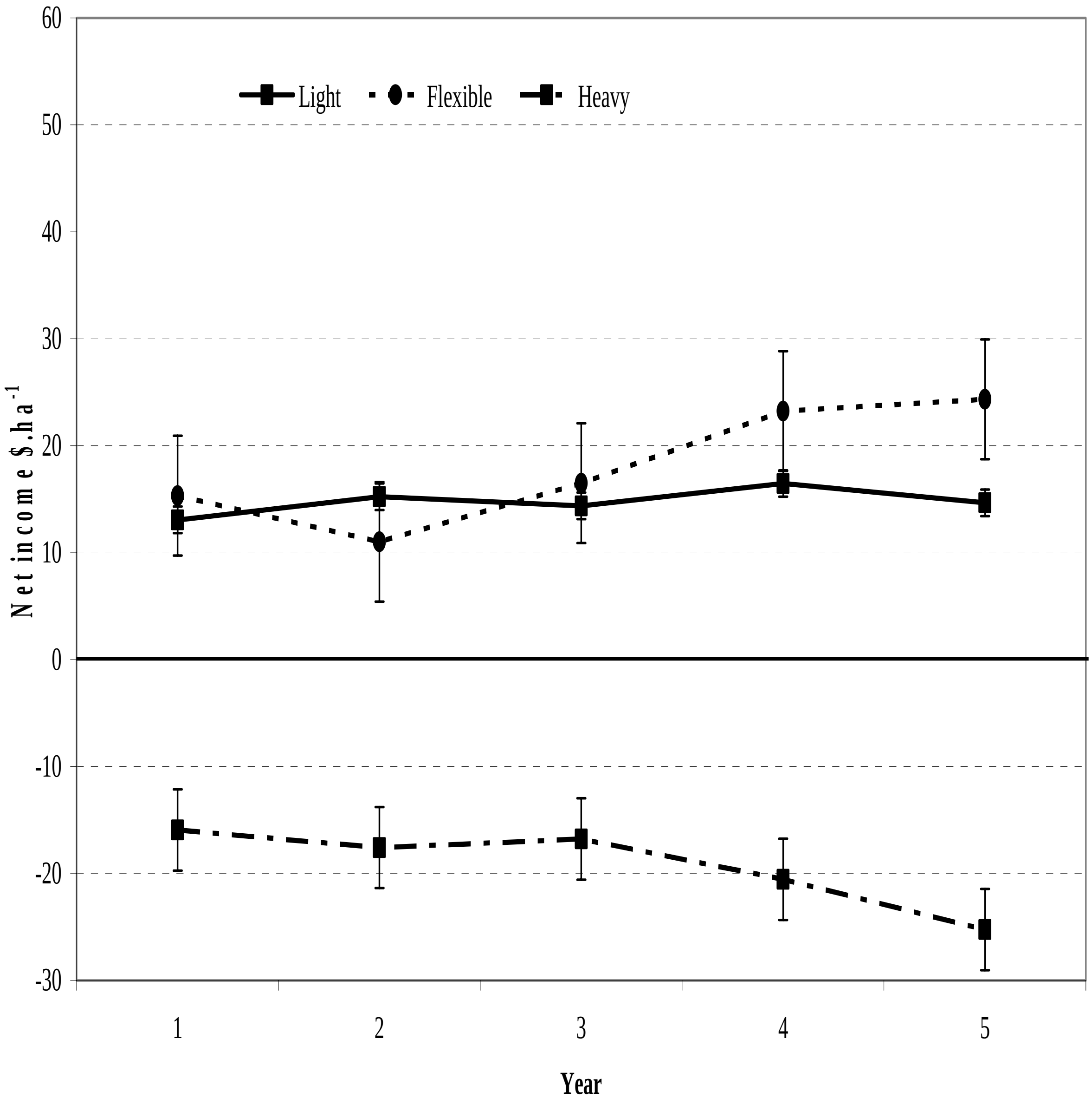

Figure 11. Variation in net income for three stocking strategies using median price.

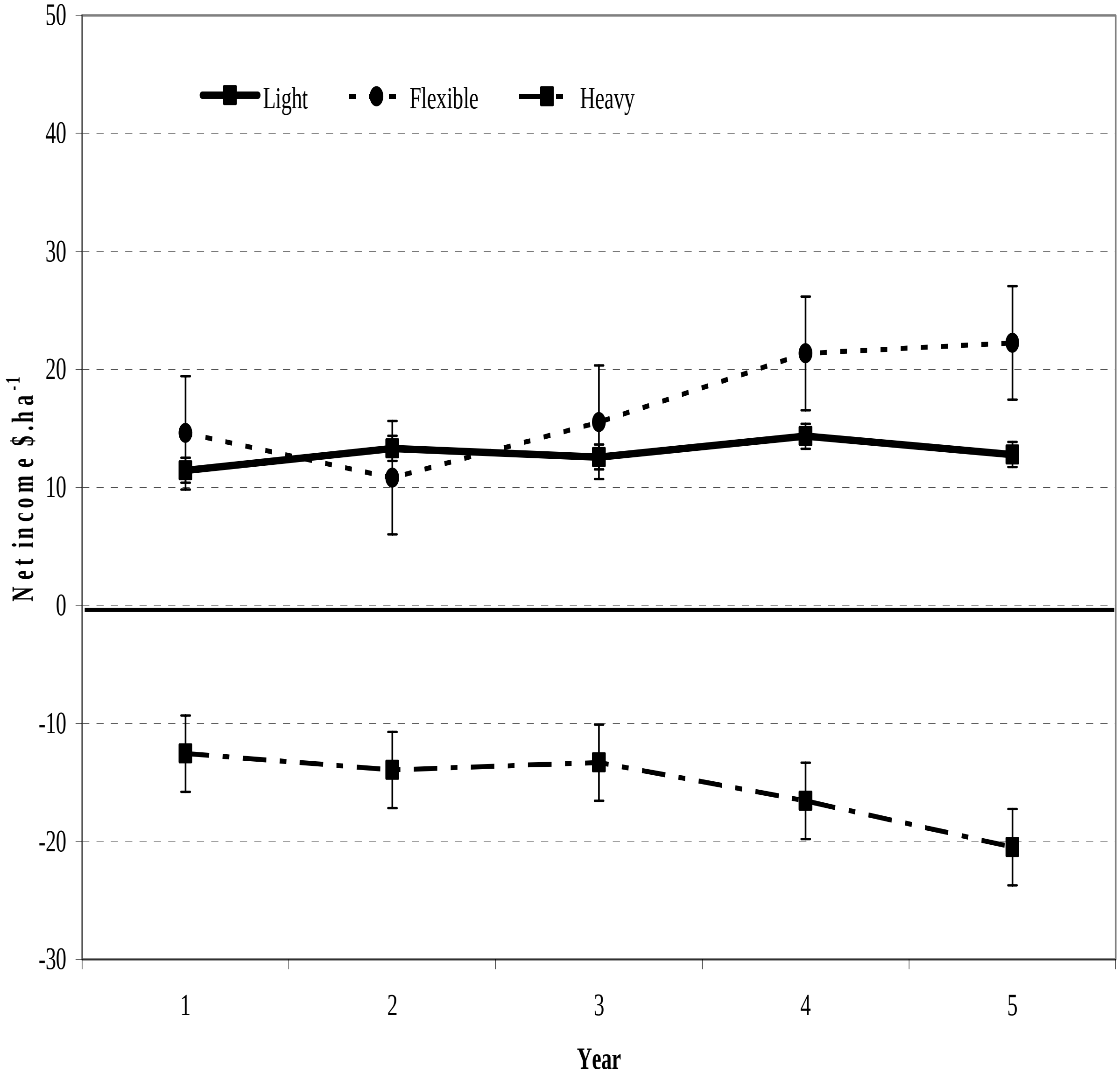

Figure 12. Variation in net income for three stocking strategies using minimum price.

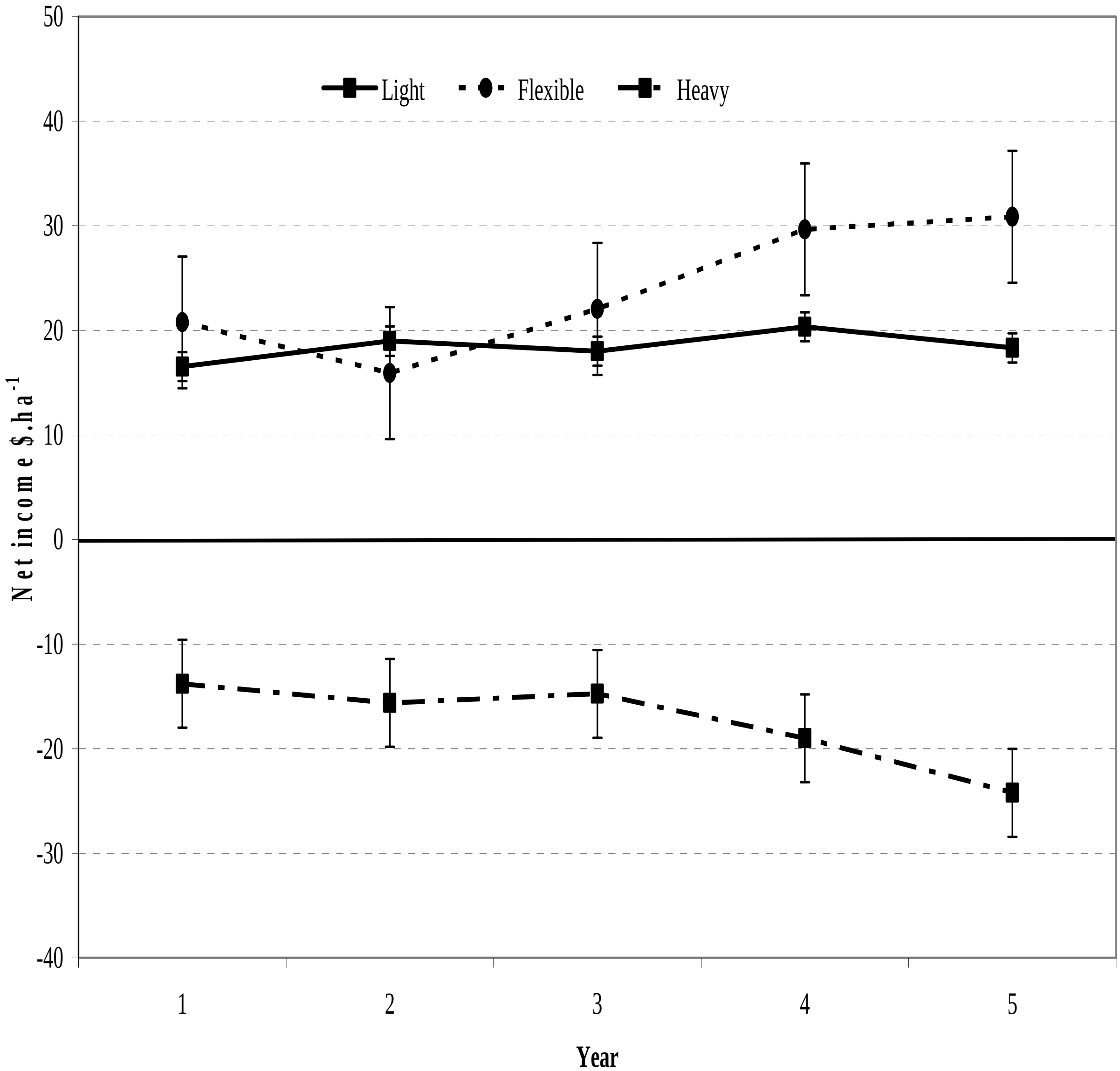

Figure 13. Variation in net income for three stocking strategies using maximum price.

CHAPTER V

MODEL APPLICATION

Biophysical and economic models for beef production can be used to evaluate impacts of short and long-term stocking decisions on range condition, animal production, and economic returns. Analyses of different stocking strategies are important for developing management strategies to increase the sustainability of cow-calf enterprises. The key benefit of using simulation models lies in the ability of the model to give indications of potential pitfall and benefits of a strategy prior to implementation, thus reducing risks of economic loss or environmental degradation.

Models support pro-active, adaptive management. By nature, models are abstractions of reality. However, well parameterized models like the one developed in this study have the potential of enhancing economic returns if appropriate management strategies be employed that are suited for the conditions (environmental and socio-economic) for which the models are developed. The robustness of a model is vital to render it useful in a wide range of economic and environmental conditions. The models should be used as a tool to inform management. The manager not the model is the decision-maker.

Applications of the model were evaluated under two broad categories; ecological and economic. Simulations were done for a wide range of stocking rates, 0.025 $AUM \cdot ha^{-1}$, 0.05 $AUM \cdot ha^{-1}$, 0.1 $AUM \cdot ha^{-1}$, 0.2 $AUM \cdot ha^{-1}$, and 0.25 $AUM \cdot ha^{-1}$, using the flexible and fixed stocking strategies to evaluate the effect of stocking rate and strategy on range condition, animal performance, and economic returns of a cow-calf enterprise.

Ecological application

Simulating effects of stocking rate on range condition

Range condition (RC) was responsive to stocking strategy (Figure 14). It was assumed that the response of the range to stocking rate would relate to the edaphic and climatic conditions of an area (NRCS 2003).

One hundred, 20-year simulations were conducted for each of the stocking rate strategies to determine the effects on RC. The simulations were done assuming no supplementation. Supplementary feeding can be used to sustain animal performance at high stocking rates. In this study, the different stocking rates were evaluated for their impact on the environment.

Light stocking rates of less than 0.05 AUM·ha^{-1} improved range condition from good to excellent i.e. from 1 to over 1.20 , regardless of whether the stocking strategy was fixed or a flexible. As stocking rate was increased from 0.05 AUM·ha^{-1} to 0.13 AUM·ha^{-1} range condition improved more under flexible stocking strategy compared to fixed strategy. At 0.17 AUM·ha^{-1} range condition declined under fixed stocking strategy while it was constant, about 1, under flexible stocking strategy for the simulation period of 20 years. Decline in range condition under high stocking rate between 0.17 AUM·ha^{-1} and 0.25 AUM·ha^{-1} was slower under flexible stocking strategy compared to decline under fixed stocking strategy. At the very heavy stocking rate of 0.25 AUM·ha^{-1} the flexible stocking strategy resulted in range condition after 20 years that was 1 unit greater than the fixed strategy.

Decline in range condition over time is slower when management uses a stocking strategy that responds to the productivity of an area. From these results it can be suggested that management will be best served if it employs a flexible stocking strategy at moderate stockings of about 0.13 $AUM \cdot ha^{-1}$ which is about 30% level of forage utilization. This corresponds to commonly recommended stocking at a moderate rate (Holechek et al 2000)

Simulating the effects of stocking strategy on BCS

BCS for a 20-year period was simulated under the flexible and fixed stocking strategies, and at seven different stocking rates (Figure 15). BCS is a rapid indicator of animal condition. Producers who understand the implication of changes in BCS to animal performance such as pregnancy rate, chances of losing the calf prior to birth or before weaning and ability to utilize forage, will do well in the management of a cow-calf enterprise. BCS declined with increase in stocking rate under fixed stocking from 6 at 0.025 $AUM \cdot ha^{-1}$ to 3 at 0.25 $AUM \cdot ha^{-1}$. Under flexible stocking strategy BCS declined from 6 to 5 at 0.025 $AUM \cdot ha^{-1}$ and 0.25 $AUM \cdot ha^{-1}$, respectively (Figure 15). Over a period of 20 years there was a general decline in body condition under heavy stocking rate a response to decline in range condition for the same period as discussed above.

BCS generally increased in late spring early summer, indicating the quality of forage at this time. Growing plants have a higher N: C ratio than mature or dead plants. By fall, plants senesce and the declining N: C ratio decreases the ability of forage to provide higher digestible energy resulting in the decline of BCS.

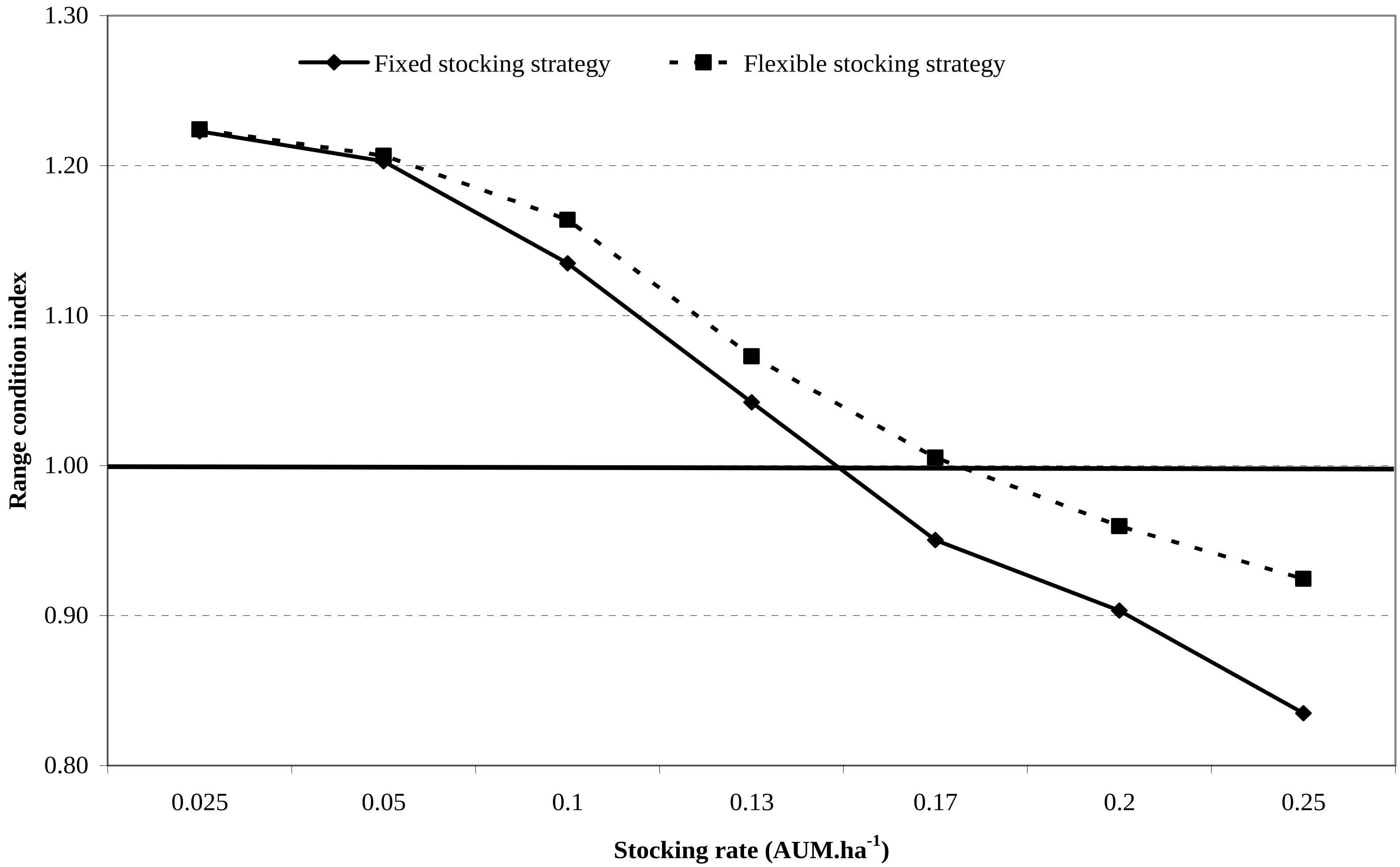

Figure 14. Response of range condition to stocking rate under two stocking strategies.

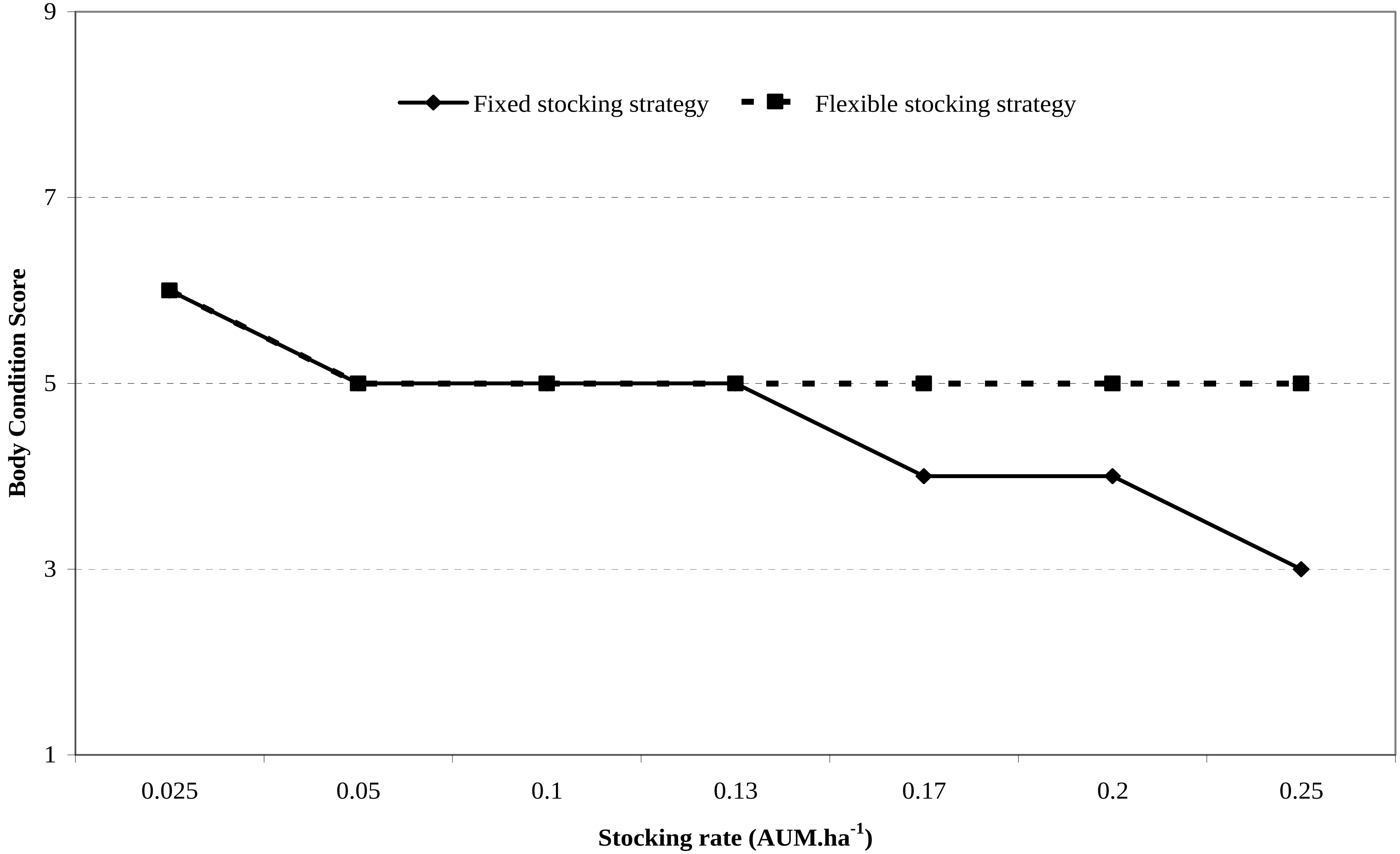

Figure 15. Response of cow BCS to stocking rate under two stocking rate strategies.

Economic applications

Investment in a cow-calf enterprise and indeed in many agricultural operations is long term. Capital investments such as infrastructure are often permanent. Prices for commodities will fluctuate mainly in response to climatic condition, advances in technology and socio-economic status of the country. As people become more informed they will seek alternative foods this can explain loss in market share of beef to pork and chicken over the years. These factors make cow-calf production business risky. Information on the potential effects of a chosen stocking strategy on net income based on historic price fluctuation could help producers reduce risks.

Effects of stocking strategy and stocking rate on net income were evaluated using two fixed grazing lease costs approaches. The first approached used a fixed lease cost per unit area of $14.00·ha^{-1} and the second approached used a fixed lease cost per cow-year of $110.00. The fixed cost per unit area approach would encourage overstocking as an increase in the number of animals in an area would result in the spreading of fixed cost in the herd, thus increasing net returns. On the other hand the fixed costs per cow year would discourage overstocking as addition of a cow results in an increase in production cost.

Under both flexible and fixed stocking strategies light stocking rates of 0.025 AUM·ha^{-1} and 0.05 AUM·ha^{-1} resulted in net losses in income when the fixed cost per unit area approach was used (Figure 16). There was positive but lower net income under the flexible light stocking strategy and light stocking when the fixed costs per cow approach was used (Figure 17). Using the fixed stocking strategy there was an increase in net income with increase in stocking rate up to 0.1 AUM· ha^{-1} then a decrease and eventually net loss as stocking rate increase from 0.13 to 0.25 AUM·ha^{-1}. On the other hand, using the flexible stocking strategy net income increased until stocking rate reached 0.17 AUM·ha^{-1} at which rate it was almost 20 times more than the income from fixed stocking strategy (Figure 17). Thereafter there was a decline in income. At the heaviest stocking rate of 0.25 AUM·ha^{-1} net income under flexible stocking rate was negative but still the losses from fixed stocking were about four times greater than from flexible stocking.

Use of the fixed stocking strategy as already mentioned significantly shifts the stocking rate at which net income can be maximized. Maximum net income was obtained between 0.05 AUM·ha^{-1} and 0.13 AUM·ha^{-1} when fixed stocking strategy was used but when flexible stocking strategy was used maximum net income was obtained between 0.1 AUM·ha^{-1} and 0.17 AUM·ha^{-1}.

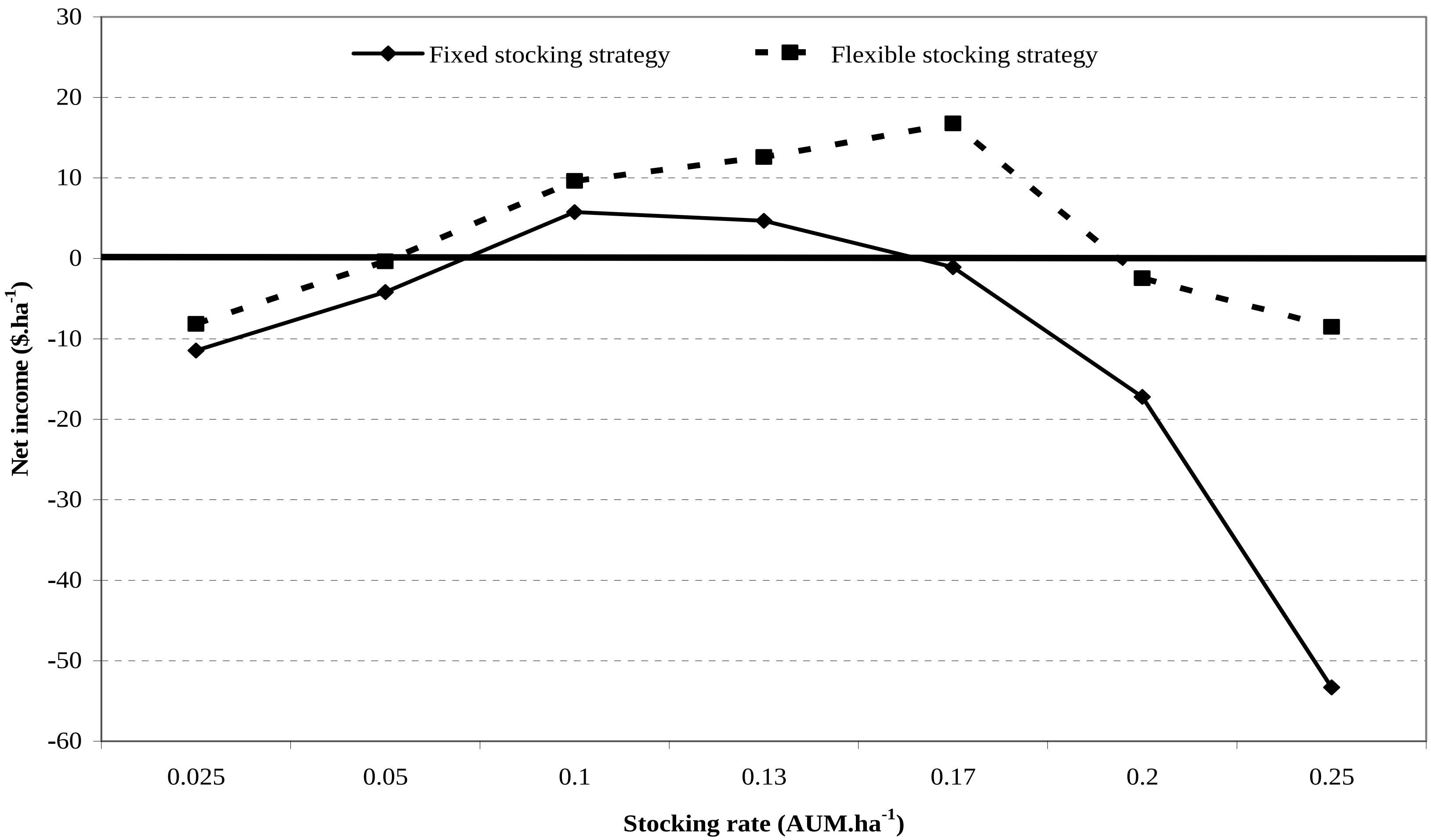

Figure 16. Effects of stocking rate on net income under two stocking strategies using fixed lease grazing cost per unit area.

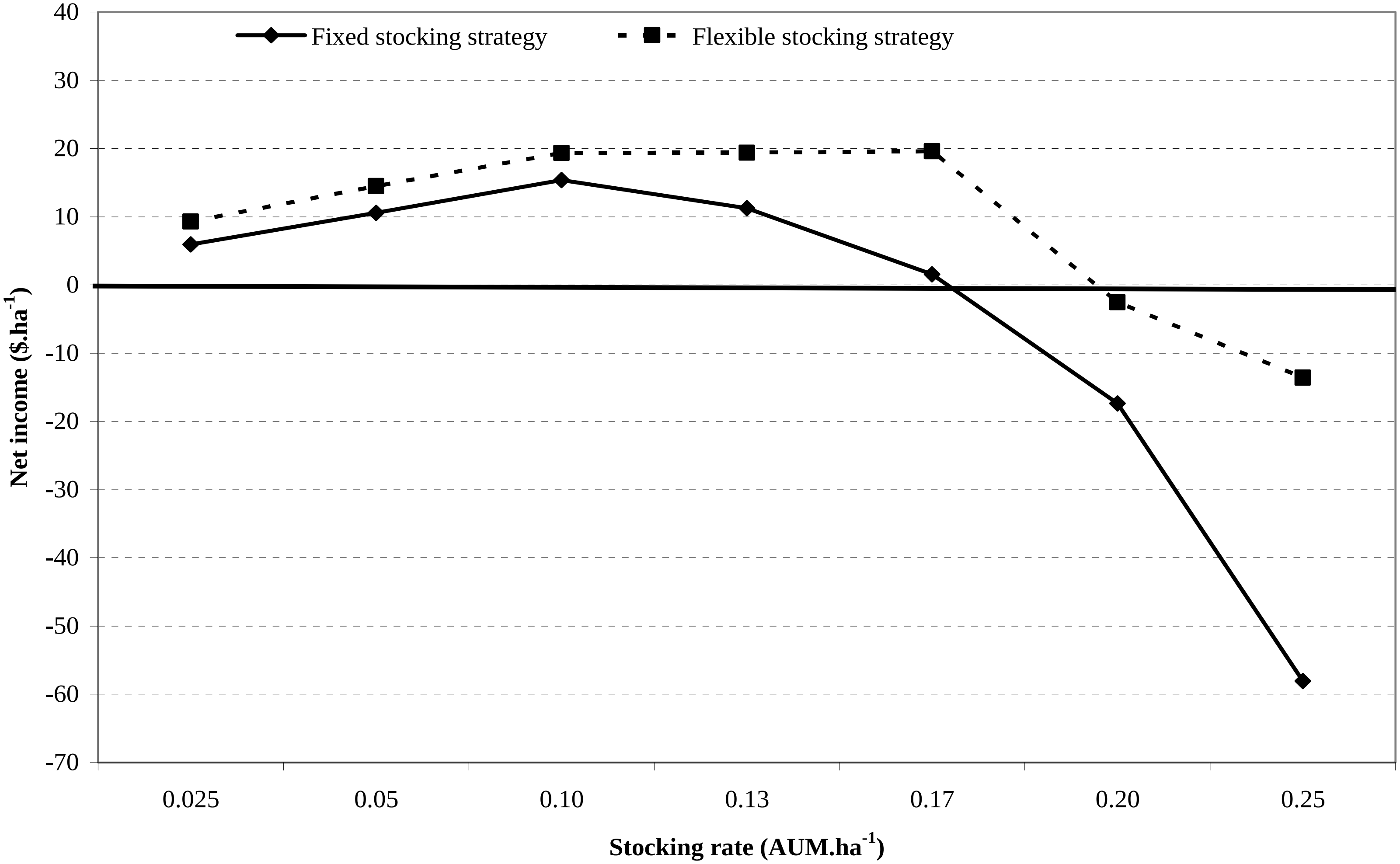

Figure 17. Effects of stocking rate on net income under two stocking strategies using fixed lease grazing cost per cow-year.

CHAPTER VI

SUMMARY AND CONCLUSION

A stochastic, compartmental model for adaptive livestock management (MALM) was developed as a tactical tool for cow-calf enterprise in the semi-arid rangelands of the Rolling Plains of Texas. The model was an offshoot from Simple Ecological Sustainability Simulator (SESS, Diaz-Solis 2003). The model is composed of three main subroutines namely; climate, forage and animal production. Two stocking strategies flexible and fixed stocking under seven stocking rate (fixed) and forage utilization levels (flexible) were evaluated for their effects on range condition, animal production and net ranch income on a hypothetical 1000 ha cow-calf ranch. The utilization levels were 5%, 10%, 20%, 30%, 40%, 50% and 60% corresponding to the fixed stocking rates of 0.025, 0.05, 0.1, 0.13, 0.17, 0.2 and 0.25 $AUM \cdot ha^{-1}$, respectively.

Field study data were obtained from published and unpublished research at the Texas A&M Experiment Station at Vernon for the Throckmorton area in the Rolling Plains of Texas. The model predicted forage production closely to what was measured at Throckmorton. The simulated GSC differed from measured GSC for specific dates, but the mean simulated GSC did not differ from measured GSC. The lack of fit was attributed to the fewer comparison data points for measured GSC rather than an overall weakness of the model.

The model adequately simulated forage and animal production. Fixed light stocking and flexible stocking resulted in cows of median BCS 5, compared to low BCS of 4 under moderate fixed stocking rate, and BCS of 3 under heavy fixed stocking. BCS declined from autumn to spring and increased from spring to autumn. Cow weight was calculated as a function of BCS; consequently the trends for weight mirrored those for BCS. Animals under light fixed stocking rates and flexible stocking were heavier (460 kg) compared to those under heavy fixed stocking (439 kg). The data from the Throckmorton (1960 to 1964) was comparable to simulated cow weight.

Under fixed stocking rates less or equal to 0.13 AUM·ha^{-1}, replacement rates were lower, between 13 and 30 %, comparable with reported rates of about 15%. Under flexible stocking rates at utilization levels below 30% the replacement rates were between 27 and 40%. When fixed stocking rate was greater than 0.17 AUM·ha^{-1} replacement rates increased to almost 80% while increasing utilization levels to 60% still resulted in replacement rates below 50% using the flexible stocking strategy. Because bred replacement heifers were used, calf crops were generally high. Calf crops were higher than the reported 85% for the area; ranging between 90% and 98% for heavy to light stocking rates respectively

Flexible stocking strategy resulted in higher net revenue (\$19.62 ha^{-1}) compared to fixed light (\$5.93 ha^{-1}) or fixed heavy (\$-17.35 ha^{-1}) stocking strategies. CV in net income was highest under heavy stocking (90%) compared to light stocking (60%) and flexible stocking (50%). Maximum net income was obtained between 0.05 AUM·ha^{-1} and 0.13 AUM·ha^{-1} when fixed stocking strategy was used but when flexible stocking strategy was used maximum net income was obtained between 0.1 AUM·ha^{-1} and 0.17 AUM·ha^{-1}.

Range condition rapidly declined under fixed heavy stocking, increased under fixed and light flexible stocking and remained constant under moderate flexible stocking. Use of light stocking has the potential of maintaining or and improving range condition over a 20-year period with peak condition reached much earlier, within 15 years. Under flexible stocking the rangeland can be maintained in fair condition for extended periods of time. Use of the heavy stocking strategy would decrease range condition rapidly, handicapping the system.

MALM is a tool that can potentially be used for decision support and as an aid for teaching producers about the consequences of different management strategies. The model does not replace the need for intimate knowledge of one's operation and should remain a tactical decision aid. It is concluded that there is great potential for models to assist in designing sustainable stocking strategies.

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APPENDIX A

MALM EQUATIONS IN ORDER OF EXECUTION

INIT CLAVFEM720 = 0

TRANSIT TIME = 13

INFLOW LIMIT = INF

CAPACITY = INF

INIT SENESCENCE = 0

INIT GSC = 5

DOCUMENT: GREEN FORAGE (KG DM/HA). INITIAL VALUE IS 0.07*0.6*NET PRIMARY PRODUCTION*RC

INIT AGE = 0.05

SA = 0.018*30.4+0.000075*30.4*AGE

IRC = 1

DOCUMENT: INITIAL RANGE CONDITION: EXC=1.25; GOOD= 1.0; FAIR=0.75 AND POOR=0.50

INIT RC = IRC

DOCUMENT: INITIAL RANGE CONDITION CLASS: EXCELLENT: 1.25; GOOD: 1.0; FAIR: 0.75; AND POOR: 0.50

M = counter (1, 13)

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

TemperatureGI = GRAPH (M)

(1.00, 0.1), (2.00, 0.5), (3.00, 0.8), (4.00, 1.00), (5.00, 1.00), (6.00, 1.10), (7.00, 0.8), (8.00, 0.8), (9.00, 1.00), (10.0, 1.00), (11.0, 0.7), (12.0, 0.5)

SC = 0

DOCUMENT: SOIL CAPACITY FOR WATER INFILTRATION AND RETENTION: HIGH= 1; MEDIUM= 0 AND LOW= -1

RUE = 6+SC

DOCUMENT: RAIN USE EFFICIENCY VALUE. RUE TAKES VALUES FROM 2 TO 7 ACCORDING TO RANGE CONDITION, SOIL DEPTH AND SLOPE. HIGH VALUES ARE FOR EXCELENT RANGE CONDITION, DEPTH SOILS AND SMALL SLOPE. (The RUE has been modified to reflect each month's water-use-efficiency)

MPPT_RF = RANDOM (0, 1)

Jan = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.6) then 19 else if (MPPT_RF<0.8) then 38 else if (MPPT_RF<0.9) then 58 else if (MPPT_RF<1) then 105 else 0

Feb = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.4) then 19 else if (MPPT_RF<0.6) then 38 else if (MPPT_RF<0.8) then 58 else if (MPPT_RF<0.9) then 77 else if (MPPT_RF<1) then 115 else 0

Mar = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.4) then 19 else if (MPPT_RF<0.7) then 38 else if (MPPT_RF<0.8) then 58 else if (MPPT_RF<0.9) then 77 else if (MPPT_RF<1) then 115 else 0

Apr = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.2) then 19 else if (MPPT_RF<0.4) then 38 else if (MPPT_RF<0.7) then 58 else if (MPPT_RF<0.8) then

77 else if (MPPT_RF<0.9) then 105 else if (MPPT_RF<0.95) then 154 else if (MPPT_RF<1) then 222 else 0

May = if (MPPT_RF<0.02) then 0 else if (MPPT_RF<0.1) then 19 else if (MPPT_RF<0.2) then 38 else if (MPPT_RF<0.4) then 58 else if (MPPT_RF<0.5) then 77 else if (MPPT_RF<0.7) then 105 else if (MPPT_RF<0.81) then 145 else if (MPPT_RF<0.96) then 192 else if (MPPT_RF<1) then 260 else 0

Jun = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.2) then 19 else if (MPPT_RF<0.3) then 38 else if (MPPT_RF<0.4) then 58 else if (MPPT_RF<0.6) then 77 else if (MPPT_RF<0.8) then 105 else if (MPPT_RF<0.9) then 135 else if (MPPT_RF<0.95) then 154 else if (MPPT_RF<1) then 222 else 0

Jul = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.3) then 19 else if (MPPT_RF<0.5) then 38 else if (MPPT_RF<0.8) then 58 else if (MPPT_RF<0.9) then 87 else if (MPPT_RF<0.95) then 135 else if (MPPT_RF<1) then 192 else 0

Aug = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.4) then 19 else if (MPPT_RF<0.6) then 38 else if (MPPT_RF<0.7) then 58 else if (MPPT_RF<0.8) then 77 else if (MPPT_RF<0.9) then 96 else if (MPPT_RF<0.95) then 135 else if (MPPT_RF<1) then 212 else 0

Sep = if(MPPT_RF<0.1) then 0 else if(MPPT_RF<0.2) then 19 else if(MPPT_RF<0.4) then 38 else if(MPPT_RF<0.5) then 58 else if(MPPT_RF<0.6) then 77 else if(MPPT_RF<0.7) then 96 else if(MPPT_RF<0.8) then 115 else if(MPPT_RF<0.9) then 154 else if(MPPT_RF<0.96) then 212 else if(MPPT_RF<1) then 279 else 0

Oct = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.3) then 19 else if (MPPT_RF<0.4) then 38 else if (MPPT_RF<0.6) then 58 else if (MPPT_RF<0.8) then 87 else if (MPPT_RF<0.9) then 120 else if (MPPT_RF<0.95) then 164 else if (MPPT_RF<1) then 270 else 0

Nov = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.5) then 19 else if (MPPT_RF<0.7) then 38 else if (MPPT_RF<0.8) then 58 else if (MPPT_RF<0.9) then 77 else if (MPPT_RF<1) then 115 else 0

Dec = if (MPPT_RF<0.1) then 0 else if (MPPT_RF<0.4) then 19 else if (MPPT_RF<0.7) then 38 else if (MPPT_RF<0.9) then 58 else if (MPPT_RF<1) then 125 else 0

MPPT = IF M=1 then Jan ELSE IF M=2 then Feb ELSE IF M=3 then Mar ELSE IF M=4 then Apr ELSE IF M=5 then May ELSE IF M=6 then Jun ELSE IF M=7 then Jul ELSE IF M=8 then Aug ELSE IF M=9 then Sep ELSE IF M=10 then Oct ELSE IF M=11 then Nov ELSE IF M=12 then Dec else 0

MNPP = RC*TemperatureGI*RUE*MPPT

DOCUMENT: Net primary production according to Rain Use Efficiency (RUE), range condition AND MONTHLY GROWTH INDEX (kg DM/month)

GSCSin = GSC*SA

DOCUMENT: Green grass losses due to other herbivores (kg DM/ha/month)

GSCSout = SENESCENCE

INIT ANPPR = 100

DOCUMENT: Grass production accumulation (kg DM/ha/month)

Ginput = MNPP

DOCUMENT: Net primary production (kg DM/ha/month)

NPPY = if (M=12) then ANPPR else 0

DOCUMENT: Unload accumulated forage each December

MWBC5 = 450

DOCUMENT: INITIAL COWS WEIGHT (SBW KG)

IBCS = 5

INIT BCS = IBCS

DOCUMENT: BODY CONDITION SCORE OF COWS PREGNANT IN 1ST MONTH

PW = GRAPH (BCS)

(1.00, 0.765), (2.00, 0.813), (3.00, 0.867), (4.00, 0.929), (5.00, 1.00), (6.00, 1.08), (7.00, 1.18), (8.00, 1.30), (9.00, 1.44)

SBW = MWBC5*PW

DOCUMENT: COWS WEIGHT ACCORDING TO BODY CONDITION SCORE (SBW KG) (FOR COHORT BECOME PREGNANT IN 1ST MONTH OF BREEDING SEASON)

GFDMD = 0.7

DOCUMENT: DRY MATTER DIGESTIBILITY OF GREEN FORAGE (0-1)

GFCFD = 1.6*(GFDMD-0.2)

GFCP = 0.12

DOCUMENT: CRUDE PROTEIN OF GREEN FORAGE (0-1)

GFCFP = 3.509*(GFCP-0.015)

GFDESI = GFCFD*GFCFP

DOCUMENT: GREEN FORAGE DESIRABILITY INDEX (DIG*PC)

DFDMD = 0.60

DOCUMENT: DRY FORAGE DIGESTIBILITY (0-1)

DFCFD = 1.67*(DFDMD-0.2)

DFCP = 0.06

DOCUMENT: DRY FORAGE CRUDE PROTEIN (0-1)

DFCFP = 3.509*(DFCP-0.015)

DFDESI = DFCFD*DFCFP

DOCUMENT: DRY FORAGE DESIRABILITY INDEX (DMD*CP)

SUMDESI = GFDESI+DFDESI

PGF = GFDESI/SUMDESI

DOCUMENT: PROPORTION OF GREEN FORAGE IN DIET (WITHOUT FORAGE AVAILAVILITY RESTRICTIONS) (0-1)

KS = (111.8973/ (1+106.16*EXP (-0.0022*MPPT*RUE)))

DOCUMENT: ASYMPTOT OF HARVESTABILITY FUNCTION (KMSEL*10= KG/HA)

HGF = (1.1*GSC)/ (KS+GSC)

DOCUMENT: GREEN FORAGE HARVESTABILITY COEFFICIENT

HGF1 = IF HGF>1 THEN 1 ELSE HGF

SRmgmt = 1

DOCUMENT: index representing the management of stocking rate:

0 = Light fixed stocking rate

1 = flexible stocking rate - stocking rate is changed during the simulation based on available forage at key decision points (month) of year

2 =Heavy fixed stocking rate - stocking rate is constant throughout the simulation

3 = light-moderate fixed stocking (0.13)

4= moderate fixed stocking (0.17)

5= very heavy fixed (0.25)

6 = ultra light fixed stocking (0.025)

7= very light fixed stocking (0.05)

SR_light_fixed = 0.1

SR_heavy_fixed = 0.2

SR_light_moderated_fixed = 0.13

SR_moderate_fixed = 0.17

SR_very_heavy_fixed = 0.25

VVLight = 0.025

Vlight = 0.05

INIT DSC = ANPPR*0.558*RC

DOCUMENT: DRY FORAGE (KG DM/HA). INITIAL VALUE IS 0.93*0.6*NET PRIMARY PRODUCTION*RC

TSCR = GSC+DSC

SR_threshold = 300

HARV% = 0.60

SR_initial = 0.25

INIT SR_AUM_HA_last_month = SR_initial

SR_AUM_HA = if(SRmgmt=0) then SR_light_fixed else if (SRmgmt=2) then SR_heavy_fixed else if(SRmgmt=3) then SR_light_moderated_fixed else if(SRmgmt=4) then SR_moderate_fixed else if(SRmgmt=5) then SR_very_heavy_fixed else if(SRmgmt=6) then VVLight else if(SRmgmt=7) then Vlight else if(SRmgmt=1) and (M=6) and (TSCR<SR_threshold) then SR_light_fixed else if (SRmgmt=1) and (M=10) and (TSCR<SR_threshold) then SR_light_fixed else if(SRmgmt=1) and (M=6) and (TSCR>SR_threshold) then HARV%*(TSCR-SR_threshold)/(5*340) else if (SRmgmt=1) and (M=10) and (TSCR>SR_threshold) then HARV%*(TSCR-SR_threshold)/(7*340) else SR_AUM_HA_last_month

DOCUMENT: STOCKING RATE (COWS/HA). This value includes heifers

GFD = IF GSC>PGF*HGF1*SBW*30.4*0.02*SR_AUM_HA THEN PGF*HGF1 ELSE ((GSC)/ (SBW*0.02*30.4*SR_AUM_HA))

DOCUMENT: PROPORTION OF GREEN FORAGE IN DIET

DNEm = GRAPH (GFD)

(0.00, 1.00), (0.1, 1.06), (0.2, 1.11), (0.3, 1.18), (0.4, 1.26), (0.5, 1.36), (0.6, 1.43), (0.7, 1.51), (0.8, 1.59), (0.9, 1.68), (1, 1.78)

DOCUMENT: Net energy for maintenance (Mcal/kg DM)

ENmVI = IF DNEm<1 THEN 0.95 ELSE DNEm

DOCUMENT: DENOMINATOR CORRECTION WHEN ENm<1.0

AMT = GRAPH (M)

(1.00, 11.9), (2.00, 13.8), (3.00, 17.0), (4.00, 20.1), (5.00, 23.1), (6.00, 25.1), (7.00, 25.5), (8.00, 26.4), (9.00, 22.7), (10.0, 19.9), (11.0, 15.6), (12.0, 13.3)

DOCUMENT: AVERAGE MONTHLY TEMPERATURE (C)

TVI = IF AMT>25 THEN 0.9 ELSE IF AMT>15 AND AMT<=25 THEN 1 ELSE IF AMT>4 AND AMT<=15 THEN 1.03 ELSE 0

DOCUMENT: TEMPERATURE EFFECT IN VOLUNTARY INTAKE

AREA = 1000

DOCUMENT: RANGELAND AREA (HA)

COWIN = SR_AUM_HA*AREA

FAT = 4

DOCUMENT: MILK FAT COMPOSITION (%)

SNF = 8.3

DOCUMENT: MILK SOLIDS NOT FAT COMPOSITION (%)

El = 0.092*FAT+0.049*SNF-0.0569

DOCUMENT: ENERGY CONTENT OF MILK (MCAL NEm/KG)

WLA1 = GRAPH (M)

(1.00, 16.0), (2.00, 20.0), (3.00, 24.0), (4.00, 28.0), (5.00, 32.0), (6.00, 36.0), (7.00, 40.0), (8.00, 44.0), (9.00, 48.0), (10.0, 4.00), (11.0, 8.00), (12.0, 12.0)

WLA2 = GRAPH (M)

(1.00, 12.0), (2.00, 16.0), (3.00, 20.0), (4.00, 24.0), (5.00, 28.0), (6.00, 32.0), (7.00, 36.0), (8.00, 40.0), (9.00, 44.0), (10.0, 48.0), (11.0, 4.00), (12.0, 8.00)

WLA3 = GRAPH (M)

(1.00, 8.00), (2.00, 12.0), (3.00, 16.0), (4.00, 20.0), (5.00, 24.0), (6.00, 28.0), (7.00, 32.0), (8.00, 36.0), (9.00, 40.0), (10.0, 44.0), (11.0, 48.0), (12.0, 4.00)

WLA4 = GRAPH (M)

(1.00, 4.00), (2.00, 8.00), (3.00, 12.0), (4.00, 16.0), (5.00, 20.0), (6.00, 24.0), (7.00, 28.0), (8.00, 32.0), (9.00, 36.0), (10.0, 40.0), (11.0, 44.0), (12.0, 48.0)

WLA5 = GRAPH (M)

(1.00, 48.0), (2.00, 4.00), (3.00, 8.00), (4.00, 12.0), (5.00, 16.0), (6.00, 20.0), (7.00, 24.0), (8.00, 28.0), (9.00, 32.0), (10.0, 36.0), (11.0, 40.0), (12.0, 44.0)

WLA6 = GRAPH (M)

(1.00, 44.0), (2.00, 48.0), (3.00, 4.00), (4.00, 8.00), (5.00, 12.0), (6.00, 16.0), (7.00, 20.0), (8.00, 24.0), (9.00, 28.0), (10.0, 32.0), (11.0, 36.0), (12.0, 40.0)

WLA7 = GRAPH (M)

(1.00, 40.0), (2.00, 44.0), (3.00, 48.0), (4.00, 4.00), (5.00, 8.00), (6.00, 12.0), (7.00, 16.0), (8.00, 20.0), (9.00, 24.0), (10.0, 28.0), (11.0, 32.0), (12.0, 36.0)

WLA8 = GRAPH (M)

(1.00, 36.0), (2.00, 40.0), (3.00, 44.0), (4.00, 48.0), (5.00, 4.00), (6.00, 8.00), (7.00, 12.0), (8.00, 16.0), (9.00, 20.0), (10.0, 24.0), (11.0, 28.0), (12.0, 32.0)

WLA9 = GRAPH (M)

(1.00, 32.0), (2.00, 36.0), (3.00, 40.0), (4.00, 44.0), (5.00, 48.0), (6.00, 4.00), (7.00, 8.00), (8.00, 12.0), (9.00, 16.0), (10.0, 20.0), (11.0, 24.0), (12.0, 28.0)

WLA10 = GRAPH (M)

(1.00, 28.0), (2.00, 32.0), (3.00, 36.0), (4.00, 40.0), (5.00, 44.0), (6.00, 48.0), (7.00, 4.00), (8.00, 8.00), (9.00, 12.0), (10.0, 16.0), (11.0, 20.0), (12.0, 24.0)

WLA11 = GRAPH (M)

(1.00, 24.0), (2.00, 28.0), (3.00, 32.0), (4.00, 36.0), (5.00, 40.0), (6.00, 44.0), (7.00, 48.0), (8.00, 4.00), (9.00, 8.00), (10.0, 12.0), (11.0, 16.0), (12.0, 20.0)

WLA12 = GRAPH (M)

(1.00, 20.0), (2.00, 24.0), (3.00, 28.0), (4.00, 32.0), (5.00, 36.0), (6.00, 40.0), (7.00, 44.0), (8.00, 48.0), (9.00, 4.00), (10.0, 8.00), (11.0, 12.0), (12.0, 16.0)

AWL = IF BS_M=1 THEN WLA1 ELSE IF BS_M=2 THEN WLA2 ELSE IF BS_M=3 THEN WLA3 ELSE IF BS_M=4 THEN WLA4 ELSE IF BS_M=5 THEN WLA5 ELSE IF BS_M=6 THEN WLA6 ELSE IF BS_M=7 THEN WLA7 ELSE IF BS_M=8 THEN WLA8 ELSE IF BS_M=9 THEN WLA9 ELSE IF BS_M=10 THEN WLA10 ELSE IF BS_M=11 THEN WLA11 ELSE IF BS_M=12 THEN WLA12 ELSE 0

n = IF AWL<33 THEN AWL ELSE 0

DOCUMENT: WEEK OF LACTATION

PKYD = 8

DOCUMENT: PEAK MILK YIELD (KG/DAY)

T = 8.5

DOCUMENT: WEEK OF PEAK LACTATION

k = 1/T

DOCUMENT: INTERMEDIATE RATE CONSTANT

a = 1/ (PKYD*k*2.718281828)

DOCUMENT: INTERMEDIATE RATE CONSTANT

Yn = n/ (a*EXP (k*n))

DOCUMENT: DAILY MILK YIELD AT n WEEK OF LACTATION (KG/DAY)

RL = El*Yn

DOCUMENT: REQUIREMENTS FOR LACTATION (MCAL/COW/DAY)

RLW = IF COWIN=0 THEN 0 ELSE RL*WMINDEX

MLDA = GRAPH (IF RLW>0 THEN AWL ELSE 0)

(0.00, 0.00), (4.00, 5.00), (8.00, 8.00), (12.0, 6.00), (16.0, 5.00), (20.0, 4.00), (24.0, 3.50), (28.0, 3.00), (32.0, 2.00), (36.0, 0.00), (40.0, 0.00), (44.0, 0.00), (48.0, 0.00)

VI = IF APM>9 THEN

((SBW^.75*(0.04997*DNEm^2+.0384)/ENmVI)*(TVI)*1+0.2*MLDA) ELSE

((SBW^.75*(0.04997*DNEm^2+.04631)/ENmVI)*(TVI)*1+0.2*MLDA)

KH = 73.672+0.00862*ANPPR+ (0.000006022*ANPPR^2)

PVI = (1.1*TSCR)/ (KH+TSCR)

DOCUMENT: HARVESTABILITY COEFFICIENT (0-1)

PVI1 = IF PVI>1 THEN 1 ELSE PVI

RI = VI*PVI1

WRI = RI

GC = WRI*GFD*SR_AUM_HA*30

DOCUMENT: Green grass consumption by cattle (kg DM/ha/month)

F = GRAPH (M)

(1.00, 0.25), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.4), (11.0, 0.4), (12.0, 0.2)

DOCUMENT: FROST AND SENESCENCE (proportion of green grass/month)

FSG = F*(GSC-GC) +0.8*SENESCENCE

DOCUMENT: Green grass that senesce (kg DM/ha/month)

GFC1 = GC/ (SR_AUM_HA*30)

DOCUMENT: GREEN FORAGE INTAKE (KG DM /HEAD/DAY)

DFC1 = WRI-GFC1

DOCUMENT: DRY FORAGE INTAKE (KG DM/HEAD/DAY)

DC = MIN (DSC, DFC1*SR_AUM_HA*30)

DOCUMENT: Dry grass consumption by cattle (kg DM/ha/month)

TRA = GRAPH (TSCR)

(0.00, 0.00), (400, 0.31), (800, 0.62), (1200, 0.93), (1600, 1.24), (2000, 1.55), (2400, 1.86), (2800, 2.16), (3200, 2.47), (3600, 2.78), (4000, 3.09)

GA = ((GSC+0.01)/ (DSC+GSC+0.01))*100

DOCUMENT: Green forage available (percentage of total forage)

DFT = SR_AUM_HA*TRA*30*(1-(GA/100))

DOCUMENT: TRAMPLING LOSSES (2 KG DM/COW/DAY)

DEADIS = 1-EXP (-0.003077*MPPT) + 0.0005*AMT

DL = DEADIS*(DSC-DC-DFT)

DOCUMENT: Long term Dry standing crop losses due to wind, litter etc. (kg DM/ha/mo)

INIT LP = 0

COW_MORTALITY_RATE = GRAPH (BCS)

(1.00, 0.05), (2.00, 0.04), (3.00, 0.007), (4.00, 0.002), (5.00, 0.001), (6.00, 0.001), (7.00, 0.001), (8.00, 0.001), (9.00, 0.001)

INIT LACTATING_NOTBULLED = 0

PREGNANCY_RATE = GRAPH (BCS)

(1.00, 0.00), (2.00, 0.3), (3.00, 0.6), (4.00, 0.8), (5.00, 0.95), (6.00, 0.95), (7.00, 0.95), (8.00, 0.95), (9.00, 0.92)

INIT PREGNANT_COWS = 250

PregIn = If M=9 then LP else 0

BUY = If M=9 and PregIn<COWIN then COWIN-PregIn else If M=9 and PregIn =0 then COWIN else 0

MortPreg = PREGNANT_COWS*COW_MORTALITY_RATE

LactIn = If M=2 then PREGNANT_COWS-MortPreg else 0

LPin = If M=4 then LACTATING_NOTBULLED*PREGNANCY_RATE else 0

MortLP = LP*COW_MORTALITY_RATE

INIT DGLA = 0

DGLM = DFT

DGLY = IF (M=12) THEN DGLA ELSE 0

INIT IACUM = 0

TCA = GC+DC

IY = IF (M=12) THEN IACUM ELSE 0

PPT = 600

DOCUMENT: MEAN ANNUAL PRECIPITATION (MM/YEAR)

INIT GE = IF PPT<451 THEN 10 ELSE IF PPT>450 AND PPT<551 THEN 12.5 ELSE 15

GUY = IF (M=12) THEN IY/NPPY*100 ELSE 0

IUTIL = GUY

OUTIL = IF M=12 THEN GE ELSE 0

OLin = if M=4 then LACTATING_NOTBULLED-LPin else 0

INIT PPTR = PPT

DOCUMENT: ANNUAL PRECIPITATION (MM/YEAR)

CV = 0.409-0.0002*PPT

IPP = IF (M=12) THEN MAX (25, NORMAL (PPT, PPT*CV)) ELSE 0

OPP = IF (M=12) THEN PPTR ELSE 0

INIT CALV07 = 0

INIT OL = 0

SellOpen = If M=9 then OL else 0

CALVES = SellOpen + PregIn

CALVO7in = if M=9 then CALVES else 0

CALV07out = If M=9 then CALV07 else 0

CALF_MORTALITY = CALV07*0.0005

INIT HEIF20 = 0

MORTFEM = LEAKAGE OUTFLOW

LEAKAGE FRACTION = CLAVFEM720*0.0005

NO-LEAK ZONE = 0

CLAVout = CONVEYOR OUTFLOW

HEIFout = HEIF20

MortOL = OL*COW_MORTALITY_RATE

INIT CALF_WEIGHT = 0

RI1 = RI

DOCUMENT: ACTUAL INTAKE (KG DM/COW/DAY)

IMCALD = RI1*DNEm

DOCUMENT: INTAKE (MCAL/COW/DAY)

CALFWEIGHT_CONVERTER = GRAPH (IMCALD)

(5.00, 160), (17.0, 250)

CWtin = If M=9 then CALFWEIGHT_CONVERTER else 0

CWout = If M=9 then CALF_WEIGHT else 0

INIT DEADCOWS = 0

Indead = MortLP+MortOL+MortPreg

Outdead = If M=9 then DEADCOWS else 0

B = 1

DOCUMENT: BRED EFFECT ON NEm REQUIREMENT

L = IF RLW=0 THEN 1 ELSE 1.2

DOCUMENT: LACTATION EFFECT ON NEm REQUIREMENT (1.2 IF LACTACTING; 1.0 IF DRY).

COMP = 0.8+ ((BCS-1)*0.05)

DOCUMENT: EFFECT OF PREVIOUS PLANE OF NUTRITION ON NEm REQUIREMENT

Tp = DELAY (AMT, 1)

DOCUMENT: PREVIOUS AVERAGE MONTHLY TEMPERATURE

A2 = 0.0007*(20-Tp)

DOCUMENT: ENERGY FOR MAINTAINANCE ADJUSTMENT FOR PREVIOUS AMBIENT TEMPERATURE

Rm = SBW^0.75*((0.077*B*L*COMP) +A2)

DOCUMENT: REQUIEREMENTS FOR MAINTAINANCE (Mcal/COW/day)

CBW = 39

DOCUMENT: EXPECTED CALF BIRTH WEIGHT (KG)

km = 0.576

DOCUMENT: CONSTANT

dp = IF APM<10 THEN APM*30 ELSE 0

DOCUMENT: DAY OF PREGNANCY

Rpreg = IF APM>9 THEN 0 ELSE CBW*(km/0.13)*(0.0585-0.0000996*dp)*EXP ((0.03233-0.0000275*dp)*dp)/1000

DOCUMENT: REQUIREMENTS FOR PREGNANCY (MCAL/COW/DAY)

DFA = GRAPH (GA)

(0.00, 0.5), (10.0, 0.52), (20.0, 0.54), (30.0, 0.56), (40.0, 0.58), (50.0, 0.6), (60.0, 0.62), (70.0, 0.64), (80.0, 0.66), (90.0, 0.68), (100, 0.7)

DOCUMENT: AVAILABLE FORAGE DRY MATTER DIGESTIBILITY (0-1)

TER = 1

Rmact = ((0.006*RI1*(0.9-DFA)) + (0.05*TER/ (GSC+3)))*SBW/4.184

DOCUMENT: GRAZING ACTIVITY REQUIREMENTS (MCAL/COW/DAY)

RmT = Rm+Rpreg+RLW+Rmact

DOCUMENT: TOTAL MAINTAINANCE REQUIREMENTS (MANT+ACTIVITY+PREGNANCY+LACTATION) (MCAL/COW/DAY)

XM = if (RmT=0) then 0 else (RI1*DNEm)/RmT

DOCUMENT: Intake expressed as times TOTAL MAINTAINANCE (#)

DEFXM = IF (XM<1) THEN (1-XM) ELSE 0

DOCUMENT: SUPPLEMENTATION FOR NO DEFICIT BETWEEN INTAKE AND REQUIREMENTS (#-MANT)

SUP100 = RmT*DEFXM

DOCUMENT: SUPPLEMENTATION FOR NO DEFFICIT BETWEEN INTAKE AND REQUIREMENTS (MCAL/COW/DAY)

SUPP_P = 0

SUPMCAL = SUP100*SUPP_P

DOCUMENT: SUPLEMENTACION (MCAL/VACA/DIA)

DMCAL = (IMCALD-RmT) + (SUPMCAL)

DOCUMENT: DIFFERENCE BETWEEN INTAKE AND REQUIREMENTS (MCAL/COW/DAY).

DMCALM = DMCAL*30

DOCUMENT: ENERGY MONTHLY DIFFERENCE BETWEEN INTAKE AND REQUIREMENTS (MCAL/COW/MONTH)

DBC = GRAPH (BCS)

(2.00, 126), (3.00, 141), (4.00, 162), (5.00, 186), (6.00, 217), (7.00, 267), (8.00, 309), (9.00, 377)

D1NTCOWS = DELAY (COWIN, 1)

IBC = GRAPH (BCS)

(1.00, 126), (2.00, 141), (3.00, 162), (4.00, 186), (5.00, 217), (6.00, 267), (7.00, 309), (8.00, 377)

IBCS1 = IF D1NTCOWS>0 AND COWIN=0 THEN BCS ELSE IF COWIN=0 AND D1NTCOWS=0 THEN 0 ELSE IF DMCALM>0 THEN DMCALM/IBC ELSE 0

DBCS1 = IF COWIN=0 THEN 0 ELSE IF DMCALM<0 THEN ABS (DMCALM*0.8/DBC) ELSE 0

INIT SENCUM = 0

ISEN = GSCSin*0.25

OSEN = IF M=12 THEN SENCUM ELSE 0

INIT TRAL = 0

ITRA = DFT

OTRA = IF M=12 THEN TRAL ELSE 0

INIT DECOMP = 0

IDEC = DL

ODEC = IF M=12 THEN DECOMP ELSE 0

WMRin = IF WMR>0 THEN 0 ELSE IF WE_MO<7 THEN WE_MO ELSE 0

WMRout = IF APM=5 THEN WMR ELSE 0

AGEP = AGE-1

AGEIN = If GSC= 0 then AGE= 0 else Min (((GSC-Ginput)/(GSC))*AGEP+1, 3)

AGEOUT = If AGE > 3 then AGE else 0

SR_in = SR_AUM_HA

SR_out = SR_AUM_HA_last_month

PROPfem = CALV07out*0.5

CLAVin = PROPfem

PSBW1 = RI1/SBW*100

DLL = GRAPH(M)

(1.00, 0.1), (2.00, 0.1), (3.00, 0.1), (4.00, 0.23), (5.00, 0.1), (6.00, 0.05), (7.00, 0.05), (8.00, 0.05), (9.00, 0.05), (10.0, 0.1), (11.0, 0.1), (12.0, 0.1)

DOCUMENT: Dry grass natural losses (proportion of dry grass/month)

S = GRAPH(M)

(1.00, 0.01), (2.00, 0.01), (3.00, 0.02), (4.00, 0.08), (5.00, 0.12), (6.00, 0.14), (7.00, 0.15), (8.00, 0.15), (9.00, 0.14), (10.0, 0.12), (11.0, 0.08), (12.0, 0.02)

DOCUMENT: Green grass losses due to other herbivores like jackrabbits, grasshoppers etc. (proportion by month)

KMSEL2 = 6.02*EXP(0.001*MPPT*RUE)

OUY = IF(M=12) THEN DGLY/NPPY*100 ELSE 0

P300 = GRAPH(GE)

(0.00, 0.01), (5.00, 0.005), (10.0, 0.00), (15.0, -0.00625), (20.0, -0.0125), (25.0, -0.0187), (30.0, -0.025), (35.0, -0.0313), (40.0, -0.0375), (45.0, -0.0437), (50.0, -0.05)

P400 = GRAPH(GE)

(0.00, 0.022), (5.00, 0.0122), (10.0, 0.00244), (15.0, -0.00484), (20.0, -0.0113), (25.0, -0.0177), (30.0, -0.0242), (35.0, -0.0306), (40.0, -0.0371), (45.0, -0.0435), (50.0, -0.05)

P500 = GRAPH(GE)

(0.00, 0.03), (50.0, -0.04)

P600 = GRAPH(GE)

(0.00, 0.04), (5.00, 0.0255), (10.0, 0.0109), (15.0, -0.00172), (20.0, -0.00862), (25.0, -0.0155), (30.0, -0.0224), (35.0, -0.0293), (40.0, -0.0362), (45.0, -0.0431), (50.0, -0.05)

P700 = GRAPH(GE)

(0.00, 0.05), (5.00, 0.0333), (10.0, 0.0167), (15.0, 0.00), (20.0, -0.00714), (25.0, -0.0143), (30.0, -0.0214), (35.0, -0.0286), (40.0, -0.0357), (45.0, -0.0429), (50.0, -0.05)

UE = IF PPT<351 THEN P300 ELSE IF PPT>350 AND PPT<451 THEN P400 ELSE IF PPT>450 AND PPT<551 THEN P500 ELSE IF PPT>550 AND PPT<651 THEN P600 ELSE IF PPT>650 THEN P700 ELSE 0

CRC = IF M=12 AND RC<1.26 AND RC>0.49 THEN RC*UE ELSE 0

INIT GEF = 0

GEFin = GUY

TINT = WRI*SR_AUM_HA*30

SRH20 = HEIF20*0.8

SRCALV = CALV07*0.2

COUNTER198588 = COUNTER(1,73)

SRH720 = CLAVFEM720*0.6

COWS = COWIN-Outdead

WEANING_WEIGHT = CWout

INIT CEW = 0

Exposed_Cows = LPin + OLin

DD = (GFD*0.7)+((1-GFD)*0.5)

AGEF = GEF/20

DOCUMENT: AVERAGE ANNUAL GRAZING EFFICIENCY (% OF ANPP)

SENS = 20

DSBW1 = DELAY(SBW,1)

DOCUMENT: SBW IN PREVIOUS MONTH (KG/COW)

WCH1 = (SBW-DSBW1)/30

DOCUMENT: CHANGE IN SBW (KG/COW/DAY)

BPM = IF APM<10 THEN APM-1 ELSE IF APM=11 THEN 9 ELSE 0

CPM = IF BPM<10 AND BPM>0 THEN BPM-1 ELSE IF APM=12 THEN 9 ELSE 0

BWL = IF AWL<33 THEN AWL-4 ELSE 0

CWL = IF AWL<33 AND AWL>4 THEN AWL-8 ELSE 0

PYEW = CEW/20*100

SENP = IF OSEN=0 THEN 0 ELSE OSEN/NPPY*100

TRAP = IF OTRA=0 THEN 0 ELSE OTRA/NPPY*100

PPT8588 = GRAPH(M)

(1.00, 9.65), (2.00, 77.0), (3.00, 95.3), (4.00, 125), (5.00, 56.6), (6.00, 86.9), (7.00, 56.9), (8.00, 34.5), (9.00, 75.9), (10.0, 98.6), (11.0, 21.3), (12.0, 4.83), (13.0, 0.00), (14.0, 29.7), (15.0, 19.8), (16.0, 83.3), (17.0, 177), (18.0, 110), (19.0, 56.6), (20.0, 29.0), (21.0, 66.3), (22.0, 208), (23.0, 66.0), (24.0, 49.8), (25.0, 33.3), (26.0, 76.5), (27.0, 37.1), (28.0, 22.9), (29.0, 107), (30.0, 144), (31.0, 35.6), (32.0, 60.2), (33.0, 73.7), (34.0, 2.54), (35.0, 15.7), (36.0, 147), (37.0, 8.89), (38.0, 17.5), (39.0, 28.2), (40.0, 61.7), (41.0, 18.3), (42.0, 84.6), (43.0, 63.0), (44.0, 25.1), (45.0, 100), (46.0, 5.08), (47.0, 19.1), (48.0, 38.4)

DEC = IF ODEC=0 THEN 0 ELSE ODEC/NPPY*100

CONTRA = DGLA+IACUM

GP = If ANPPR = 0 then 0 else (SR_AUM_HA*365*12)/(ANPPR)

DISAPP = GRAPH(GP)

(0.1, 27.7), (0.2, 16.3), (0.3, 13.2), (0.4, 10.4), (0.5, 9.08), (0.6, 8.17), (0.7, 7.26), (0.8, 6.81), (0.9, 6.36)

DNI = DISAPP-WRI

CEWin = IF WMRin>0 THEN 1 ELSE 0

SRBULLS = (COWIN/15)*1.25

INIT Stocking_rate = 0

SRHA = SR_AUM_HA

REP = 1

SENESCENCE(t) = SENESCENCE(t - dt) + (GSCSin - GSCSout) * dt

GSC(t) = GSC(t - dt) + (MNPP - GSCSin - GC - FSG) * dt

DOCUMENT: GREEN FORAGE (KG DM/HA). INITIAL VALUE IS 0.07*0.6*NET PRIMARY PRODUCTION*RC

AGE(t) = AGE(t - dt) + (AGEIN - AGEOUT) * dt

RC(t) = RC(t - dt) + (CRC) * dt

DOCUMENT: INITIAL RANGE CONDITION CLASS: EXCELLENT: 1.25; GOOD: 1.0; FAIR: 0.75; AND POOR: 0.50

ANPPR(t) = ANPPR(t - dt) + (Ginput - NPPY) * dt

DOCUMENT: Grass production accumulation (kg DM/ha/month)

BCS(t) = BCS(t - dt) + (IBCS1 - DBCS1) * dt

DOCUMENT: BODY CONDITION SCORE OF COWS

DSC(t) = DSC(t - dt) + (FSG - DC - DFT - DL) * dt

DOCUMENT: DRY FORAGE (KG DM/HA). INITIAL VALUE IS 0.93*0.6*NET PRIMARY PRODUCTION*RC

SR_AUM_HA_last_month(t) = SR_AUM_HA_last_month(t - dt) + (SR_in - SR_out) * dt

WMR(t) = WMR(t - dt) + (WMRin - WMRout) * dt

LP(t) = LP(t - dt) + (LPin - MortLP - PregIn) * dt

LACTATING_NOTBULLED(t) = LACTATING_NOTBULLED(t - dt) + (LactIn - OLin - LPin) * dt

PREGNANT_COWS(t) = PREGNANT_COWS(t - dt) + (BUY + PregIn - LactIn - MortPreg) * dt

DGLA(t) = DGLA(t - dt) + (DGLM - DGLY) * dt

IACUM(t) = IACUM(t - dt) + (TCA - IY) * dt

GE(t) = GE(t - dt) + (IUTIL - OUTIL) * dt

PPTR(t) = PPTR(t - dt) + (IPP - OPP) * dt

DOCUMENT: ANNUAL PRECIPITATION (MM/YEAR)

CALV07(t) = CALV07(t - dt) + (CALVO7in - CALV07out - CALF_MORTALITY) * dt

OL(t) = OL(t - dt) + (OLin - SellOpen - MortOL) * dt

HEIF20(t) = HEIF20(t - dt) + (CLAVout - HEIFout) * dt

CALF_WEIGHT(t) = CALF_WEIGHT(t - dt) + (CWtin - CWout) * dt

DEADCOWS(t) = DEADCOWS(t - dt) + (Indead - Outdead) * dt

SENCUM(t) = SENCUM(t - dt) + (ISEN - OSEN) * dt

TRAL(t) = TRAL(t - dt) + (ITRA - OTRA) * dt

DECOMP(t) = DECOMP(t - dt) + (IDEC - ODEC) * dt

GEF(t) = GEF(t - dt) + (GEFin) * dt

CEW(t) = CEW(t - dt) + (CEWin) * dt

Stocking_rate(t) = Stocking_rate(t - dt) + (SRHA) * dt

CLAVFEM720(t) = CLAVFEM720(t - dt) + (CLAVin - CLAVout - MORTFEM) * dt

SA = 0.018*30.4+0.000075*30.4*AGE

M = counter(1,13)

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

TemperatureGI = GRAPH(M)

(1.00, 0.1), (2.00, 0.5), (3.00, 0.8), (4.00, 1.00), (5.00, 1.00), (6.00, 1.10), (7.00, 0.8), (8.00, 0.8), (9.00, 1.00), (10.0, 1.00), (11.0, 0.7), (12.0, 0.5)

RUE = 6+SC

DOCUMENT: RAIN USE EFFICIENCY VALUE. RUE TAKES VALUES FROM 2 TO 7 ACCORDING TO RANGE CONDITION, SOIL DEPTH AND SLOPE. HIGH VALUES ARE FOR EXCELENT RANGE CONDITION, DEPTH SOILS AND SMALL SLOPE. (The RUE has been modified to reflect each month's water-use-efficiency)

MPPT_RF = RANDOM(0,1)

Jan = if(MPPT_RF<0.1) then 0 else if(MPPT_RF<0.6) then 19 else if(MPPT_RF<0.8) then 38 else if(MPPT_RF<0.9) then 58 else if(MPPT_RF<1) then 105 else 0

Feb = if(MPPT_RF<0.1) then 0 else if(MPPT_RF<0.4) then 19 else if(MPPT_RF<0.6) then 38 else if(MPPT_RF<0.8) then 58 else if(MPPT_RF<0.9) then 77 else if(MPPT_RF<1) then 115 else 0

Mar = if(MPPT_RF<0.1) then 0 else if(MPPT_RF<0.4) then 19 else if(MPPT_RF<0.7) then 38 else if(MPPT_RF<0.8) then 58 else if(MPPT_RF<0.9) then 77 else if(MPPT_RF<1) then 115 else 0

Apr = if(MPPT_RF<0.1) then 0 else if(MPPT_RF<0.2) then 19 else if(MPPT_RF<0.4) then 38 else if(MPPT_RF<0.7) then 58 else if(MPPT_RF<0.8) then 77 else if(MPPT_RF<0.9) then 105 else if(MPPT_RF<0.95) then 154 else if(MPPT_RF<1) then 222 else 0

May = if(MPPT_RF<0.02) then 0 else if(MPPT_RF<0.1) then 19 else if(MPPT_RF<0.2) then 38 else if(MPPT_RF<0.4) then 58 else if(MPPT_RF<0.5) then 77 else if(MPPT_RF<0.7) then 105 else if(MPPT_RF<0.81) then 145 else if(MPPT_RF<0.96) then 192 else if(MPPT_RF<1) then 260 else 0

Jun = if(MPPT_RF<0.1) then 0 else if(MPPT_RF<0.2) then 19 else if(MPPT_RF<0.3) then 38 else if(MPPT_RF<0.4) then 58 else if(MPPT_RF<0.6) then 77 else if(MPPT_RF<0.8) then 105 else if(MPPT_RF<0.9) then 135 else if(MPPT_RF<0.95) then 154 else if(MPPT_RF<1) then 222 else 0

Jul = if(MPPT_RF<0.1) then 0 else if(MPPT_RF<0.3) then 19 else if(MPPT_RF<0.5) then 38 else if(MPPT_RF<0.8) then 58 else if(MPPT_RF<0.9) then 87 else if(MPPT_RF<0.95) then 135 else if(MPPT_RF<1) then 192 else 0

Aug = if(MPPT_RF<0.1) then 0 else if(MPPT_RF<0.4) then 19 else if(MPPT_RF<0.6) then 38 else if(MPPT_RF<0.7) then 58 else if(MPPT_RF<0.8) then 77 else if(MPPT_RF<0.9) then 96 else if(MPPT_RF<0.95) then 135 else if(MPPT_RF<1) then 212 else 0

Sep = if(MPPT_RF<0.1) then 0 else if(MPPT_RF<0.2) then 19 else if(MPPT_RF<0.4) then 38 else if(MPPT_RF<0.5) then 58 else if(MPPT_RF<0.6) then 77 else if(MPPT_RF<0.7) then 96 else if(MPPT_RF<0.8) then 115 else if(MPPT_RF<0.9) then 154 else if(MPPT_RF<0.96) then 212 else if(MPPT_RF<1) then 279 else 0

Oct = if(MPPT_RF<0.1) then 0 else if(MPPT_RF<0.3) then 19 else if(MPPT_RF<0.4) then 38 else if(MPPT_RF<0.6) then 58 else if(MPPT_RF<0.8) then 87 else if(MPPT_RF<0.9) then 120 else if(MPPT_RF<0.95) then 164 else if(MPPT_RF<1) then 270 else 0

Nov = if(MPPT_RF<0.1) then 0 else if(MPPT_RF<0.5) then 19 else if(MPPT_RF<0.7) then 38 else if(MPPT_RF<0.8) then 58 else if(MPPT_RF<0.9) then 77 else if(MPPT_RF<1) then 115 else 0

Dec = if(MPPT_RF<0.1) then 0 else if(MPPT_RF<0.4) then 19 else if(MPPT_RF<0.7) then 38 else if(MPPT_RF<0.9) then 58 else if(MPPT_RF<1) then 125 else 0

MPPT = IF M=1 then Jan ELSE IF M=2 then Feb ELSE IF M=3 then Mar ELSE IF M=4 then Apr ELSE IF M=5 then May ELSE IF M=6 then Jun ELSE IF M=7 then Jul ELSE IF M=8 then Aug ELSE IF M=9 then Sep ELSE IF M=10 then Oct ELSE IF M=11 then Nov ELSE IF M=12 then Dec else 0

MNPP = RC*TemperatureGI*RUE*MPPT

DOCUMENT: Net primary production according to Rain Use Efficiency (RUE) , range condition AND MONTHLY GROWTH INDEX (kg DM/month)

GSCSin = GSC*SA

DOCUMENT: Green grass losses due to other herbivores (kg DM/ha/month)

GSCSout = SENESCENCE

Ginput = MNPP

DOCUMENT: Net primary production (kg DM/ha/month)

NPPY = if(M=12) then ANPPR else 0

DOCUMENT: Unload accumulated forage each December

SBW = MWBC5*PW

DOCUMENT: COWS WEIGHT ACCORDING TO BODY CONDITION SCORE (SBW KG)

GFCFD = 1.6*(GFDMD-0.2)

GFCFP = 3.509*(GFCP-0.015)

GFDESI = GFCFD*GFCFP

DOCUMENT: GREEN FORAGE DESIRABILITY INDEX (DIG*PC)

DFCFD = 1.67*(DFDMD-0.2)

DFCFP = 3.509*(DFCP-0.015)

DFDESI = DFCFD*DFCFP

DOCUMENT: DRY FORAGE DESIRABILITY INDEX (DMD*CP)

SUMDESI = GFDESI+DFDESI

PGF = GFDESI/SUMDESI

DOCUMENT: PROPORTION OF GREEN FORAGE IN DIET (WITHOUT FORAGE AVAILAVILITY RESTRICTIONS) (0-1)

KS = (111.8973/(1+106.16*EXP(-0.0022*MPPT*RUE)))

DOCUMENT: ASYMPTOT OF HARVESTABILITY FUNCTION (KMSEL*10= KG/HA)

HGF = (1.1*GSC)/(KS+GSC)

DOCUMENT: GREEN FORAGE HARVESTABILITY COEFFICIENT

HGF1 = IF HGF>1 THEN 1 ELSE HGF

TSCR = GSC+DSC

SR_AUM_HA = if(SRmgmt=0) then SR_light_fixed else if (SRmgmt=2) then SR_heavy_fixed else if(SRmgmt=3) then SR_light_moderated_fixed else if(SRmgmt=4) then SR_moderate_fixed else if(SRmgmt=5) then SR_very_heavy_fixed else if(SRmgmt=6) then VVLight else if(SRmgmt=7) then Vlight else if(SRmgmt=1) and (M=6) and (TSCR<SR_threshold) then SR_light_fixed else if (SRmgmt=1) and (M=10) and (TSCR<SR_threshold) then SR_light_fixed else if(SRmgmt=1) and (M=6) and (TSCR>SR_threshold) then HARV%*(TSCR-SR_threshold)/(5*340) else if (SRmgmt=1) and (M=10) and (TSCR>SR_threshold) then HARV%*(TSCR-SR_threshold)/(7*340) else SR_AUM_HA_last_month

DOCUMENT: STOCKING RATE (COWS/HA). This value includes heifers

GFD = IF GSC>PGF*HGF1*SBW*30.4*0.02*SR_AUM_HA THEN PGF*HGF1 ELSE ((GSC)/(SBW*0.02*30.4*SR_AUM_HA))

DOCUMENT: PROPORTION OF GREEN FORAGE IN DIET

DNEm = GRAPH(GFD)

(0.00, 1.00), (0.1, 1.06), (0.2, 1.11), (0.3, 1.18), (0.4, 1.26), (0.5, 1.36), (0.6, 1.43), (0.7, 1.51), (0.8, 1.59), (0.9, 1.68), (1, 1.78)

DOCUMENT: Net energy for maintenance (Mcal/kg DM)

ENmVI = IF DNEm<1 THEN 0.95 ELSE DNEm

DOCUMENT: DENOMINATOR CORRECTION WHEN ENm<1.0

AMT = GRAPH(M)

(1.00, 11.9), (2.00, 13.8), (3.00, 17.0), (4.00, 20.1), (5.00, 23.1), (6.00, 25.1), (7.00, 25.5), (8.00, 26.4), (9.00, 22.7), (10.0, 19.9), (11.0, 15.6), (12.0, 13.3)

DOCUMENT: AVERAGE MONTHLY TEMPERATURE (C)

TVI = IF AMT>25 THEN 0.9 ELSE IF AMT>15 AND AMT<=25 THEN 1 ELSE IF AMT>4 AND AMT<=15 THEN 1.03 ELSE 0

DOCUMENT: TEMPERATURE EFFECT IN VOLUNTARY INTAKE

COWIN = SR_AUM_HA*AREA

El = 0.092*FAT+0.049*SNF-0.0569

DOCUMENT: ENERGY CONTENT OF MILK (MCAL NEm/KG)

k = 1/T

DOCUMENT: INTERMEDIATE RATE CONSTANT

a = 1/(PKYD*k*2.718281828)

DOCUMENT: INTERMEDIATE RATE CONSTANT

Yn = n/(a*EXP(k*n))

DOCUMENT: DAILY MILK YIELD AT n WEEK OF LACTATION (KG/DAY)

RL = El*Yn

DOCUMENT: REQUIREMENTS FOR LACTATION (MCAL/COW/DAY)

RLW = IF COWIN=0 THEN 0 ELSE RL*WMINDEX

MLDA = GRAPH(IF RLW>0 THEN AWL ELSE 0)

(0.00, 0.00), (4.00, 5.00), (8.00, 8.00), (12.0, 6.00), (16.0, 5.00), (20.0, 4.00), (24.0, 3.50), (28.0, 3.00), (32.0, 2.00), (36.0, 0.00), (40.0, 0.00), (44.0, 0.00), (48.0, 0.00)

VI = IF APM>9 THEN

((SBW^.75*(0.04997*DNEm^2+.0384)/ENmVI)*(TVI)*1+0.2*MLDA) ELSE

((SBW^.75*(0.04997*DNEm^2+.04631)/ENmVI)*(TVI)*1+0.2*MLDA)

KH = 73.672+0.00862*ANPPR+(0.000006022*ANPPR^2)

PVI = (1.1*TSCR)/(KH+TSCR)

DOCUMENT: HARVESTABILITY COEFFICIENT (0-1)

PVI1 = IF PVI>1 THEN 1 ELSE PVI

RI = VI*PVI1

WRI = RI

GC = WRI*GFD*SR_AUM_HA*30

DOCUMENT: Green grass consumption by cattle (kg DM/ha/month)

F = GRAPH(M)

(1.00, 0.25), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.4), (11.0, 0.4), (12.0, 0.2)

DOCUMENT: FROST AND SENESCENCE (proportion of green grass/month)

FSG = F*(GSC-GC)+0.8*SENESCENCE

DOCUMENT: Green grass that senesce (kg DM/ha/month)

GFC1 = GC/(SR_AUM_HA*30)

DOCUMENT: GREEN FORAGE INTAKE (KG DM /HEAD/DAY)

DFC1 = WRI-GFC1

DOCUMENT: DRY FORAGE INTAKE (KG DM/HEAD/DAY)

DC = MIN(DSC,DFC1*SR_AUM_HA*30)

DOCUMENT: Dry grass consumption by cattle (kg DM/ha/month)

TRA = GRAPH(TSCR)

(0.00, 0.00), (400, 0.31), (800, 0.62), (1200, 0.93), (1600, 1.24), (2000, 1.55), (2400, 1.86), (2800, 2.16), (3200, 2.47), (3600, 2.78), (4000, 3.09)

GA = ((GSC+0.01)/(DSC+GSC+0.01))*100

DOCUMENT: Green forage available (percentage of total forage)

DFT = SR_AUM_HA*TRA*30*(1-(GA/100))

DOCUMENT: TRAMPLING LOSSES (2 KG DM/COW/DAY)

DEADIS = 1-EXP(-0.003077*MPPT) + 0.0005*AMT

DL = DEADIS*(DSC-DC-DFT)

DOCUMENT: Long term Dry standing crop losses due to wind, litter etc. (kg DM/ha/mo)

COW_MORTALITY_RATE = GRAPH(BCS)

(1.00, 0.05), (2.00, 0.04), (3.00, 0.007), (4.00, 0.002), (5.00, 0.001), (6.00, 0.001), (7.00, 0.001), (8.00, 0.001), (9.00, 0.001)

PREGNANCY_RATE = GRAPH(BCS)

(1.00, 0.00), (2.00, 0.3), (3.00, 0.6), (4.00, 0.8), (5.00, 0.95), (6.00, 0.95), (7.00, 0.95), (8.00, 0.95), (9.00, 0.92)

PregIn = If M=9 then LP else 0

BUY = If M=9 and PregIn<COWIN then COWIN-PregIn else If M=9 and PregIn =0 then COWIN else 0

MortPreg = PREGNANT_COWS*COW_MORTALITY_RATE

LactIn = If M=2 then PREGNANT_COWS-MortPreg else 0

LPin = If M=4 then LACTATING_NOTBULLED*PREGNANCY_RATE else 0

MortLP = LP*COW_MORTALITY_RATE

DGLM = DFT

DGLY = IF(M=12) THEN DGLA ELSE 0

TCA = GC+DC

IY = IF(M=12) THEN IACUM ELSE 0

GUY = IF(M=12) THEN IY/NPPY*100 ELSE 0

IUTIL = GUY

OUTIL = IF M=12 THEN GE ELSE 0

OLin = if M=4 then LACTATING_NOTBULLED-LPin else 0

CV = 0.409-0.0002*PPT

IPP = IF(M=12) THEN MAX(25,NORMAL(PPT,PPT*CV)) ELSE 0

OPP = IF(M=12) THEN PPTR ELSE 0

SellOpen = If M=9 then OL else 0

CALVES = SellOpen + PregIn

CALVO7in = if M=9 then CALVES else 0

CALV07out = If M=9 then CALV07 else 0

CALF_MORTALITY = CALV07*0.0005

MORTFEM = LEAKAGE OUTFLOW

LEAKAGE FRACTION = CLAVFEM720*0.0005

CLAVout = CONVEYOR OUTFLOW

HEIFout = HEIF20

MortOL = OL*COW_MORTALITY_RATE

RI1 = RI

DOCUMENT: ACTUAL INTAKE (KG DM/COW/DAY) FOR

IMCALD = RI1*DNEm

DOCUMENT: INTAKE (MCAL/COW/DAY)

CALFWEIGHT_CONVERTER = GRAPH(IMCALD)

(5.00, 160), (17.0, 250)

CWtin = If M=9 then CALFWEIGHT_CONVERTER else 0

CWout = If M=9 then CALF_WEIGHT else 0

Indead = MortLP+MortOL+MortPreg

Outdead = If M=9 then DEADCOWS else 0

L = IF RLW=0 THEN 1 ELSE 1.2

DOCUMENT: LACTATION EFFECT ON NEm REQUIREMENT (1.2 IF LACTACTING; 1.0 IF DRY).

COMP = 0.8+((BCS-1)*0.05)

DOCUMENT: EFFECT OF PREVIOUS PLANE OF NUTRITION ON NEm REQUIREMENT

Tp = DELAY(AMT,1)

DOCUMENT: PREVIOUS AVERAGE MONTHLY TEMPERATURE

A2 = 0.0007*(20-Tp)

DOCUMENT: ENERGY FOR MAINTAINANCE ADJUSTMENT FOR PREVIOUS AMBIENT TEMPERATURE

Rm = SBW^0.75*((0.077*B*L*COMP)+A2)

DOCUMENT: REQUIEREMENTS FOR MAINTAINANCE (Mcal/COW/day)

Rpreg = IF APM>9 THEN 0 ELSE CBW*(km/0.13)*(0.0585-0.0000996*dp)*EXP((0.03233-0.0000275*dp)*dp)/1000

DOCUMENT: REQUIREMENTS FOR PREGNANCY (MCAL/COW/DAY)

DFA = GRAPH(GA)

(0.00, 0.5), (10.0, 0.52), (20.0, 0.54), (30.0, 0.56), (40.0, 0.58), (50.0, 0.6), (60.0, 0.62), (70.0, 0.64), (80.0, 0.66), (90.0, 0.68), (100, 0.7)

DOCUMENT: AVAILABLE FORAGE DRY MATTER DIGESTIBILITY (0-1)

Rmact = ((0.006*RI1*(0.9-DFA))+(0.05*TER/(GSC+3)))*SBW/4.184

DOCUMENT: GRAZING ACTIVITY REQUIREMENTS (MCAL/COW/DAY)

RmT = Rm+Rpreg+RLW+Rmact

DOCUMENT: TOTAL MAINTAINANCE REQUIREMENTS (MANT+ACTIVITY+PREGNANCY+LACTATION) (MCAL/COW/DAY)

XM = if(RmT=0) then 0 else (RI1*DNEm)/RmT

DOCUMENT: Intake expressed as times TOTAL MAINTAINANCE (#)

DMCAL = (IMCALD-RmT)+(SUPMCAL)

DOCUMENT: DIFFERENCE BETWEEN INTAKE AND REQUIREMENTS (MCAL/COW/DAY).

DMCALM = DMCAL*30

DOCUMENT: ENERGY MONTHLY DIFFERENCE BETWEEN INTAKE AND REQUIREMENTS (MCAL/COW/MONTH)

DBC = GRAPH(BCS)

(2.00, 126), (3.00, 141), (4.00, 162), (5.00, 186), (6.00, 217), (7.00, 267), (8.00, 309), (9.00, 377)

D1NTCOWS = DELAY(COWIN,1)

IBC = GRAPH(BCS)

(1.00, 126), (2.00, 141), (3.00, 162), (4.00, 186), (5.00, 217), (6.00, 267), (7.00, 309), (8.00, 377)

IBCS1 = IF D1NTCOWS>0 AND COWIN=0 THEN BCS ELSE IF COWIN=0 AND D1NTCOWS=0 THEN 0 ELSE IF DMCALM>0 THEN DMCALM/IBC ELSE 0

DBCS1 = IF COWIN=0 THEN 0 ELSE IF DMCALM<0 THEN ABS(DMCALM*0.8/DBC) ELSE 0

ISEN = GSCSin*0.25

OSEN = IF M=12 THEN SENCUM ELSE 0

ITRA = DFT

OTRA = IF M=12 THEN TRAL ELSE 0

IDEC = DL

ODEC = IF M=12 THEN DECOMP ELSE 0

WMRin = IF WMR>0 THEN 0 ELSE IF WE_MO<7 THEN WE_MO ELSE 0

WMRout = IF APM=5 THEN WMR ELSE 0

AGEP = AGE-1

AGEIN = If GSC= 0 then AGE= 0 else Min (((GSC-Ginput)/(GSC))*AGEP+1, 3)

AGEOUT = If AGE > 3 then AGE else 0

SR_in = SR_AUM_HA

SR_out = SR_AUM_HA_last_month

PROPfem = CALV07out*0.5

CLAVin = PROPfem

PSBW1 = RI1/SBW*100

DLL = GRAPH(M)

(1.00, 0.1), (2.00, 0.1), (3.00, 0.1), (4.00, 0.23), (5.00, 0.1), (6.00, 0.05), (7.00, 0.05), (8.00, 0.05), (9.00, 0.05), (10.0, 0.1), (11.0, 0.1), (12.0, 0.1)

DOCUMENT: Dry grass natural losses (proportion of dry grass/month)

S = GRAPH(M)

(1.00, 0.01), (2.00, 0.01), (3.00, 0.02), (4.00, 0.08), (5.00, 0.12), (6.00, 0.14), (7.00, 0.15), (8.00, 0.15), (9.00, 0.14), (10.0, 0.12), (11.0, 0.08), (12.0, 0.02)

DOCUMENT: Green grass losses due to other herbivores like jackrabbits, grasshoppers etc. (proportion by month)

KMSEL2 = 6.02*EXP(0.001*MPPT*RUE)

OUY = IF(M=12) THEN DGLY/NPPY*100 ELSE 0

P300 = GRAPH(GE)

(0.00, 0.01), (5.00, 0.005), (10.0, 0.00), (15.0, -0.00625), (20.0, -0.0125), (25.0, -0.0187), (30.0, -0.025), (35.0, -0.0313), (40.0, -0.0375), (45.0, -0.0437), (50.0, -0.05)

P400 = GRAPH(GE)

(0.00, 0.022), (5.00, 0.0122), (10.0, 0.00244), (15.0, -0.00484), (20.0, -0.0113), (25.0, -0.0177), (30.0, -0.0242), (35.0, -0.0306), (40.0, -0.0371), (45.0, -0.0435), (50.0, -0.05)

P500 = GRAPH(GE)

(0.00, 0.03), (50.0, -0.04)

P600 = GRAPH(GE)

(0.00, 0.04), (5.00, 0.0255), (10.0, 0.0109), (15.0, -0.00172), (20.0, -0.00862), (25.0, -0.0155), (30.0, -0.0224), (35.0, -0.0293), (40.0, -0.0362), (45.0, -0.0431), (50.0, -0.05)

P700 = GRAPH(GE)

(0.00, 0.05), (5.00, 0.0333), (10.0, 0.0167), (15.0, 0.00), (20.0, -0.00714), (25.0, -0.0143), (30.0, -0.0214), (35.0, -0.0286), (40.0, -0.0357), (45.0, -0.0429), (50.0, -0.05)

UE = IF PPT<351 THEN P300 ELSE IF PPT>350 AND PPT<451 THEN P400 ELSE IF PPT>450 AND PPT<551 THEN P500 ELSE IF PPT>550 AND PPT<651 THEN P600 ELSE IF PPT>650 THEN P700 ELSE 0

CRC = IF M=12 AND RC<1.26 AND RC>0.49 THEN RC*UE ELSE 0

GEFin = GUY

TINT = WRI*SR_AUM_HA*30

SRH20 = HEIF20*0.8

SRCALV = CALV07*0.2

COUNTER198588 = COUNTER(1,73)

SRH720 = CLAVFEM720*0.6

COWS = COWIN-Outdead

WEANING_WEIGHT = CWout

Exposed_Cows = LPin + OLin

DD = (GFD*0.7)+((1-GFD)*0.5)

AGEF = GEF/20

DOCUMENT: AVERAGE ANNUAL GRAZING EFFICIENCY (% OF ANPP)

DSBW1 = DELAY(SBW,1)

DOCUMENT: SBW IN PREVIOUS MONTH (KG/COW)

WCH1 = (SBW-DSBW1)/30

DOCUMENT: CHANGE IN SBW (KG/COW/DAY)

APPENDIX B

Table B-1. Simulated number of calves weaned under fixed and flexible stocking strategy at each stocking rate (AUM·ha^{-1}) and at each forage utilization level (%), respectively.

	Stocking rate and % forage utilization levels													
YEAR	0.025	0.05	0.10	5%	10%	20%	30%	40%	50%	60%	0.13	0.17	0.20	0.25
1	25	49	97	36	59	111	156	203	204	264	126	162	189	232
2	25	49	97	36	65	114	156	199	218	253	127	164	190	231
3	25	49	98	38	66	114	158	200	230	252	126	163	189	229
4	25	49	98	40	75	120	163	202	200	242	127	163	189	227
5	25	49	98	40	75	121	160	201	222	238	126	164	188	226
6	25	49	98	40	75	127	164	195	215	240	125	163	188	226
7	25	49	98	43	78	129	173	188	217	238	126	162	189	224
8	25	49	98	43	81	132	175	197	229	240	127	163	188	223
9	25	49	98	44	81	137	166	204	226	227	127	164	189	223
10	25	49	98	43	80	133	172	201	216	251	127	164	188	220
11	25	49	98	44	81	138	180	201	206	234	127	163	187	215
12	25	49	98	43	83	138	181	197	198	259	126	162	185	215
13	25	49	98	43	82	143	180	184	225	225	126	162	184	214
14	25	49	98	43	83	144	186	195	206	223	127	162	184	212
15	25	49	98	42	84	143	180	203	213	212	127	161	183	209
16	25	49	98	43	81	153	188	198	204	225	126	163	182	210
17	25	49	98	44	84	149	180	198	211	227	127	161	183	206
18	25	49	98	45	84	152	181	189	215	216	126	161	182	202
19	25	49	98	44	82	154	186	205	213	206	126	160	182	201
20	25	49	98	45	82	156	184	199	206	204	127	160	180	194

APPENDIX C

Table C-1. Simulated calf weaning weight under fixed and flexible stocking strategy at each stocking rate (AUM·ha^{-1}) and at each forage utilization level (%), respectively.

	Stocking rate and % forage utilization levels													
YEAR	0.025	0.05	0.10	5%	10%	20%	30%	40%	50%	60%	0.13	0.17	0.20	0.25
1	222.1	221.5	217.3	222.9	213.8	219.4	217.6	216.6	212.8	209.4	214.5	211.5	208.8	206.8
2	220.8	219.2	220.6	224.9	220.4	219.5	214.8	212.7	213.3	207.3	215.3	214.7	207.3	204.9
3	221.7	221.8	216.6	223.5	220.9	220.5	215.8	216.7	213.0	208.4	216.1	210.7	208.1	203.8
4	220.5	218.6	219.5	222.6	220.3	222.7	219.7	214.8	210.0	213.1	210.3	212.9	206.4	203.4
5	225.5	219.5	215.8	225.4	221.6	218.8	218.6	214.8	213.9	206.9	212.4	212.0	205.8	204.4
6	223.9	224.6	217.7	221.8	224.0	216.6	218.0	215.4	215.1	210.9	214.9	211.2	210.6	203.6
7	224.2	221.0	220.6	220.1	222.6	221.0	219.9	211.9	215.4	207.8	220.7	214.4	209.0	202.7
8	223.7	219.4	219.9	220.9	223.2	217.8	218.0	213.2	208.2	206.6	217.5	215.6	212.3	206.9
9	227.5	222.2	218.7	223.3	229.1	219.8	216.2	211.8	212.4	210.5	215.1	214.6	205.4	202.1
10	225.6	220.9	218.3	226.5	223.0	219.4	215.8	217.4	210.9	206.0	217.5	210.9	207.4	199.8
11	221.5	221.8	222.8	224.2	218.5	221.6	216.9	213.5	212.5	211.2	220.8	212.0	208.8	201.0
12	221.6	219.9	214.7	223.9	224.0	221.4	219.6	216.3	210.7	210.5	214.8	208.2	206.8	200.9
13	223.7	227.0	223.1	221.4	220.4	218.6	219.4	206.7	212.9	212.1	218.9	210.6	209.4	200.8
14	224.1	222.8	222.1	219.4	218.6	217.7	216.5	208.8	208.7	210.8	217.3	208.9	206.8	197.0
15	222.6	221.5	214.7	225.1	219.8	217.4	215.1	211.9	211.7	204.6	215.3	213.5	207.3	200.7
16	222.9	224.8	218.4	225.9	223.8	221.5	219.1	217.1	213.9	205.8	217.7	210.9	206.6	198.8
17	227.2	221.5	221.2	221.3	221.8	218.3	214.4	214.2	212.0	210.4	215.3	213.9	205.8	192.9
18	224.5	226.2	219.1	224.3	222.4	216.7	217.1	215.9	210.4	207.2	215.4	208.5	210.1	193.8
19	220.8	223.3	224.5	222.7	222.3	217.5	217.8	214.6	207.5	209.5	217.7	208.4	201.6	195.3
20	224.7	220.8	213.5	224.4	220.5	218.5	215.4	211.8	210.9	210.4	212.3	211.6	202.5	195.8

APPENDIX D

Table D-1. Simulated number of replacement heifers under fixed and flexible stocking strategy at each stocking rate (AUM·ha^{-1}) and at each forage utilization level (%), respectively.

	Stocking rate and % forage utilization levels													
YEAR	0.025	0.05	0.10	5%	10%	20%	30%	40%	50%	60%	0.13	0.17	0.20	0.25
1	4	8	26	8	14	29	50	75	118	91	40	69	98	155
2	4	9	24	6	14	31	51	76	84	92	40	66	100	161
3	4	9	25	6	13	28	46	72	113	94	38	70	98	168
4	3	8	23	8	14	32	51	66	95	95	43	71	102	165
5	4	10	24	7	15	29	53	64	95	99	46	71	107	172
6	4	8	24	8	14	33	54	74	100	98	40	72	101	177
7	4	8	22	5	11	31	49	84	93	97	35	70	103	180
8	3	8	22	8	13	24	53	74	94	95	38	66	99	177
9	3	9	22	5	16	34	58	78	90	98	36	61	108	186
10	3	9	21	7	14	35	59	73	83	104	37	70	112	197
11	3	8	20	7	14	32	51	60	114	105	39	70	115	198
12	4	8	21	7	15	34	59	85	78	109	39	77	116	206
13	4	8	21	7	13	33	47	85	99	109	36	76	117	206
14	4	7	23	8	16	43	61	74	90	115	37	82	128	214
15	3	8	23	6	16	32	46	73	99	112	38	73	125	211
16	3	7	25	6	12	34	45	65	101	113	34	77	125	216
17	3	7	21	8	14	37	54	80	99	119	41	79	128	226
18	3	8	21	6	11	36	52	64	100	119	40	87	122	228
19	4	8	19	6	14	39	64	92	107	121	36	85	129	236
20	3	7	22	6	13	35	59	63	86	120	38	83	135	237

APPENDIX E

Table E-1. Simulated shrunk body weight of cull cows at weaning under fixed and flexible stocking strategy at each stocking rate (AUM·ha^{-1}) and at each forage utilization level (%), respectively.

	Stocking rate and % forage utilization levels													
YEAR	0.025	0.05	0.10	5%	10%	20%	30%	40%	50%	60%	0.13	0.17	0.20	0.25
1	477.1	472.0	462.3	482.1	470.4	465.4	455.5	448.3	436.6	429.4	453.2	439.9	430.1	413.5
2	479.4	472.1	461.7	481.1	472.9	464.7	455.1	443.9	433.5	428.6	452.0	437.3	430.1	415.5
3	479.4	477.9	459.9	482.9	475.7	465.1	451.2	447.3	434.8	432.3	452.0	436.4	426.4	412.0
4	480.0	474.0	463.4	481.9	476.3	467.2	459.5	444.2	439.9	430.0	448.9	439.7	422.8	411.9
5	481.8	473.0	460.7	483.8	477.9	467.6	456.7	447.8	438.1	428.3	448.3	436.4	424.4	409.6
6	477.7	477.8	461.2	481.9	476.7	466.0	451.8	447.5	440.8	427.3	451.9	439.3	427.8	409.2
7	478.3	476.0	465.8	478.7	478.4	471.8	452.5	448.0	439.9	428.0	453.6	442.2	425.3	404.7
8	484.2	477.4	459.3	482.6	478.7	469.9	454.5	438.7	437.3	424.4	452.0	439.1	426.8	407.5
9	485.9	472.0	464.1	478.4	473.8	468.4	455.7	442.9	435.0	429.8	454.9	441.0	423.2	401.2
10	488.8	475.3	464.1	482.6	473.4	466.0	453.6	445.7	439.2	434.0	453.1	439.9	419.0	399.0
11	481.0	476.3	465.4	482.1	473.4	467.4	452.8	446.6	438.8	432.6	450.8	435.1	421.3	395.9
12	477.3	477.3	465.2	484.2	477.9	467.3	453.2	446.6	432.7	430.4	452.7	432.3	423.2	396.9
13	478.1	478.6	466.3	476.6	475.2	463.5	453.6	447.0	439.0	430.2	456.3	432.1	417.9	394.5
14	482.7	478.2	462.8	483.1	475.6	462.8	454.0	442.9	436.2	431.3	454.1	431.0	413.2	393.0
15	485.7	480.5	462.9	483.4	474.6	465.9	454.6	441.9	436.8	431.4	455.9	438.0	414.0	392.2
16	484.0	482.3	459.7	483.9	474.8	467.2	463.1	447.5	437.7	431.3	454.2	432.3	413.2	387.6
17	482.7	477.2	465.1	481.6	474.2	466.2	456.1	450.2	432.7	429.2	448.8	429.6	411.5	386.2
18	479.0	474.4	465.2	479.1	474.8	464.8	456.7	449.7	433.6	423.7	454.1	428.5	413.0	380.8
19	480.2	477.5	470.9	481.8	475.7	464.5	450.8	444.4	429.1	426.2	453.5	430.6	410.3	375.5
20	484.4	478.3	465.2	485.3	474.6	460.9	450.2	445.7	435.6	428.6	452.6	425.8	409.3	373.5

APPENDIX F

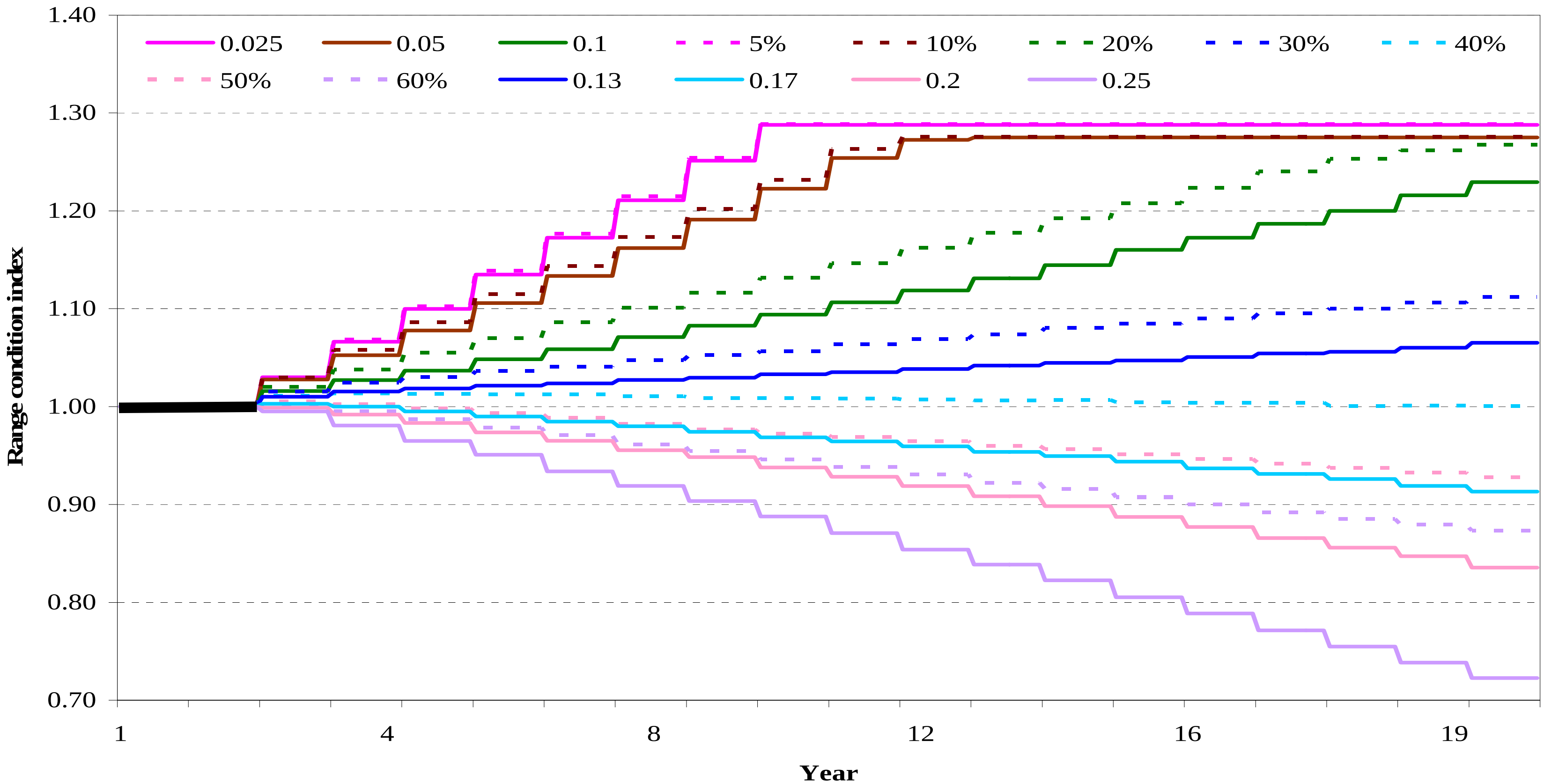

Figure F-1. Simulated trend in range condition under fixed and flexible stocking strategy at each stocking rate (AUM·ha^{-1}) and at each forage utilization level (%), respectively

APPENDIX G

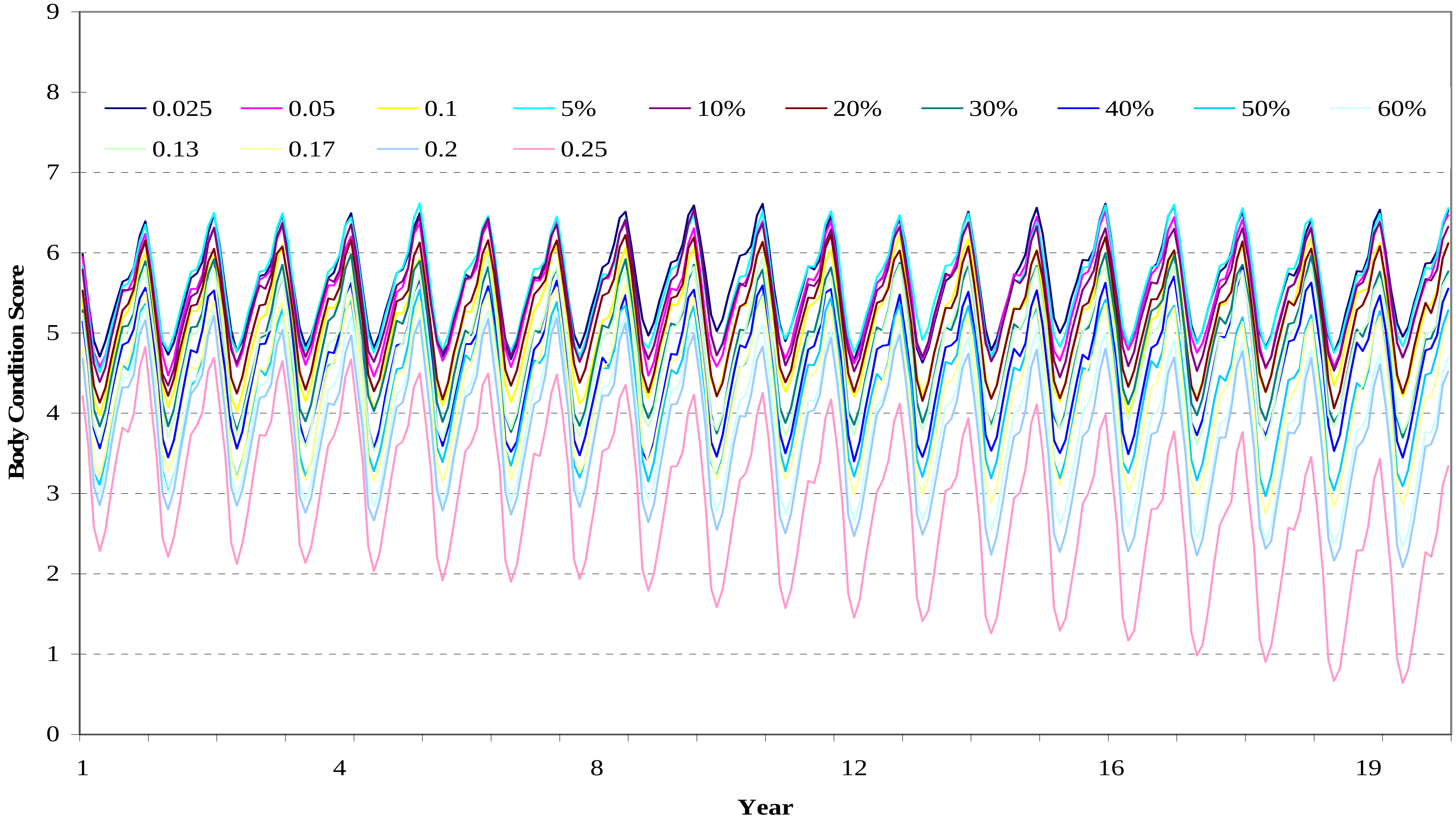

Figure G-1. Simulated trend in cow body condition score under fixed and flexible stocking strategy at each stocking rate (AUM·ha^{-1}) and at each forage utilization level (%), respectively

VITA

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- Stiles Chair Scholar, College of Agriculture Texas A&M University, TX, 2002
- Franklin Wasko Graduate Scholarship, Dept Range Ecol& Mgt Texas A&M University, 2003-2004
- Hiram Wild Botany Prize: Best student Biological Sciences University of Zimbabwe, 1994

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- Grassland Society of Southern Africa
- Zimbabwe Animal and Grassland Society
- Zimbabwe Association of Applied Mathematics