ABSTRACT

Arid and semi-arid regions have increasingly become the subject of much research and debate by scientists. By their very nature, these regions characteristically exhibit extremes which complicate the implementation of effective management strategies that ensure sustainable productivity and economic output. Namibia is one such region where low and highly variable rainfall conditions and fluctuating productivity pose a challenge to managers of commercial livestock enterprises, who seek to optimise economic benefits while controlling the negative effect on herd production and income of unpredictable and unfavourable climatic events.

Various management approaches are proposed as a means of exploiting periods of abundant productivity and so optimising income from herd production, while controlling for the effects of drought conditions. To analyse the effects of these various offtake strategies, a rainfall-driven plant-herbivore simulation model is used. The model comprises components simulating vegetation and herbivore dynamics. The vegetation component incorporates soil moisture and nutrient allocation to plant parts. The herbivore dynamics sub-model comprises age and sex classes, population dynamics and animal energy requirements which govern accumulated fat reserves. The model is adapted to account for climatic and vegetation attributes specific to Namibia. An economic component including a seasonal monthly price structure is developed, and a dynamic feedback governing management decisions is incorporated.

The much debated issue of whether to maintain a constant stocking rate or to track climatic variation by employing a variable stocking level is investigated, with the performance of management strategies incorporating these approaches ranked according to various factors, including annual returns, associated risk and annual stock mortality. The economic consequences of the timing of offtake are investigated, with the simulation of management strategies that implement de-stocking in the face of anticipated drought conditions. A dynamic projection of expected income allows the impact of forecasting potential economic gains on decision-making to be analysed.

Results indicate that the performance of management strategies is not as dependent on climatic and seasonal price variability as was originally expected, with the application of a constant stocking level proving to be the most favourable strategy in terms of economic gain and variability of income. Tracking climatic variation by adapting stocking levels does not provide the improvement in economic returns from a livestock production system that was anticipated, although this approach is successful in effecting a significant reduction in annual stock mortality. Further results show the sensitivity of income to the long-term average stocking level characterising the management strategies investigated, as well as to the elasticity of the underlying price structure.

The results of this study indicate that the implementation of management strategies designed to track climatic variation does not offer significant economic advantages over the application of a constant stocking approach.

PREFACE

The work described in this thesis was conducted in the School of Mathematics, Statistics and Information Technology, University of Natal, Pietermaritzburg under the supervision of Prof. J.W. Hearne.

These studies represent original work by the author and have not otherwise been submitted in any form to another university. Where use has been made of the work of others it is duly acknowledged in the text.

2/10/01

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There are so many people who have supported, encouraged and assisted me on the road that has lead me to this point, without whom the journey would certainly have been more difficult. To those not acknowledged individually, I thank them for the role that they have played.

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To Dr Andrew Illius and Mr Julian Derry of the University of Edinburgh, I extend my gratitude for the valuable time and energy that they have invested in this project. I thank them for their patience in answering my many questions, and their willingness to assist me and to share their extensive knowledge with me. Thanks also go to Professor David Ward, for his initial suggestions and assistance in getting this project off the ground.

My thanks to the staff at the Namibian Meteorological Services and the Namibian Meat Board for the information and data provided.

On a personal note, I give honour to God, by whom I have been richly blessed. I am sincerely grateful to Neil Jardine, whose confidence in me afforded me the opportunity to reach this point. I express my love and appreciation to my family and friends, who have always stood by me, encouraged, cared for and sustained me. Their support has been invaluable and I am truly grateful, particularly to my parents, for their love, patience and understanding.

LIST OF FIGURES AND TABLES

CHAPTER ONE

INTRODUCTION

1.1. INTRODUCTION

The past decade has seen increasing debate amongst ecologists and environmental scientists regarding the approaches practised by rangeland managers with respect to stocking rate strategies. It has been argued that the oft-implemented policy of maintaining a single, conservative stocking rate for large herbivores is inappropriate for regions characterised by highly variable rainfall. It is proposed that a constant stocking approach should be replaced by a fluctuating stocking rate that is dependent on climatic factors. These so-called "opportunistic" strategies are intuitively expected to provide higher economic returns, with an added advantage of protecting rangeland condition and avoiding the consequences of overgrazing.

This study aims to clarify aspects of the ongoing controversy surrounding the implementation of stocking options in highly variable climates. It is proposed that the implementation of adaptive stocking levels in response to rainfall conditions could effect improved productivity and subsequent financial returns, while reducing drought-induced stock mortality. In undertaking this investigation, a stochastic, rainfall-driven simulation model is used, with plant and animal dynamics modelled as sub-components. This detailed plant-herbivore model allows the consequences of various management strategies that incorporate the approaches of constant stocking and so-called adaptive stocking (or "tracking") policies in a commercial livestock production system to be examined.

This model was developed by Illius, Derry and Gordon (1998) for implementation in Zimbabwe, and adapted for use in Namibia, a country with typically arid and semi-arid climatic conditions of low rainfall incidence with high variability. Seasonal variation in meat prices makes the timing of offtake crucial to the economic returns for commercial farmers. There exists an opportunity cost of reducing stock too early in the erroneous anticipation of drought conditions. This opportunity cost must be balanced against the risk of maintaining stock levels and subsequent insufficient rainfall to support these levels, with consequential stock losses.

1.2. AN OVERVIEW OF NAMIBIA

1.2.1. General

Namibia, located between the 17th and 29th degree of southern latitude in south-western Africa, is a dry and sparsely populated country. Its location, in combination with the cold land masses resulting from the cool Benguela current on the west coast, is responsible for the sparse and erratic rainfall that the country typically experiences. It is bounded by the South Atlantic Ocean to the west, Angola to the north, Botswana to the east and South Africa to the south, and covers an area of 824 268 km^2. (Namibia, 1994). Forty-five percent of Namibia's land area is comprised of commercial livestock enterprises, with National Parks and communal land constituting fifteen percent and forty percent of the remaining area respectively (Cumming, 1990).

1.2.2. Topography and Climate

Namibia has a warm, dry climate, with the hottest months in January and February. The rainfall season occurs during the summer months. Rainfall is typically sparse and erratic, and prolonged periods of drought are characteristic. Stafford Smith and Foran (1992) offer two alternative definitions of drought, one from a strictly climatic perspective and one in forage composition sense. The former defines drought as a period when rainfall, or a rainfall-related growth index, falls below some statistical level. The latter describes a period during which palatable plant biomass is inadequate to satisfy the intake requirements of herbivores in the system. The second definition is questionable in that changes in forage composition can be effected by events other than low rainfall, namely over-stocking in the present or recent past or long-term land degradation of production potential. As such, Stafford Smith and Foran (1992) propose that drought conditions be defined as those under which expected pasture growth is insufficient to satisfy average intake requirements at given local stocking rates.

Rainfall over most of Namibia averages less than 400 mm per annum. The high rainfall variability that typifies most of the country's rainfall pattern is a contributing factor to the difficulty of correctly implementing any management options that rely on climatic forecasting. The rainfall distribution ranges from close to zero over the hyperarid zone of the Namib desert, to approximately 600mm per annum in the northern part of the country, which encompasses the Etosha National Park and boasts a rich variety of wildlife. The country can be described as arid to semi-arid over 97% of its total land mass, with the remainder considered to be sub-tropical.

The country can be broadly divided into three climatic zones, namely the northern, central and southern regions. The sub-humid northern region experiences relatively high annual rainfall (600-800 mm per annum) with decreased variability in rainfall (co-efficient of variation ±0.36) in contrast to the southern region where rainfall is in the range 100-200 mm per annum and highly erratic (co-efficient of variation ±0.7). The central plateau incorporates the capital, Windhoek, where a mean annual rainfall of 346mm is experienced, with a co-efficient of variation of 34.4%.

Figure 1 shows that, on average, for a rainfall year starting in September, about half of the year's average annual rainfall has fallen by the end of January, 70% by the end of February, and 89% by the end of March. Thus it is possible for livestock managers to recognise the potential occurrence of a drought should no significant rainfall occurred by the end of January, and react accordingly. The consequences of farmer's responses to anticipated drought conditions are an aspect of livestock management strategies that is examined in this study.

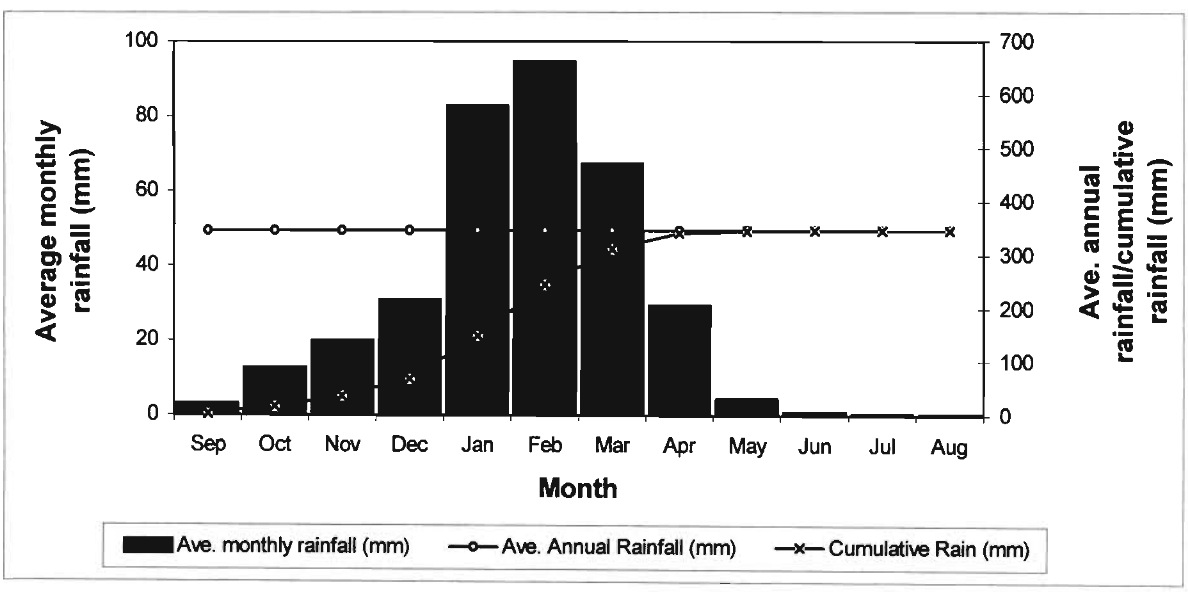

Figure 1. Long-term average monthly rainfall pattern for the Windhoek rainfall site.

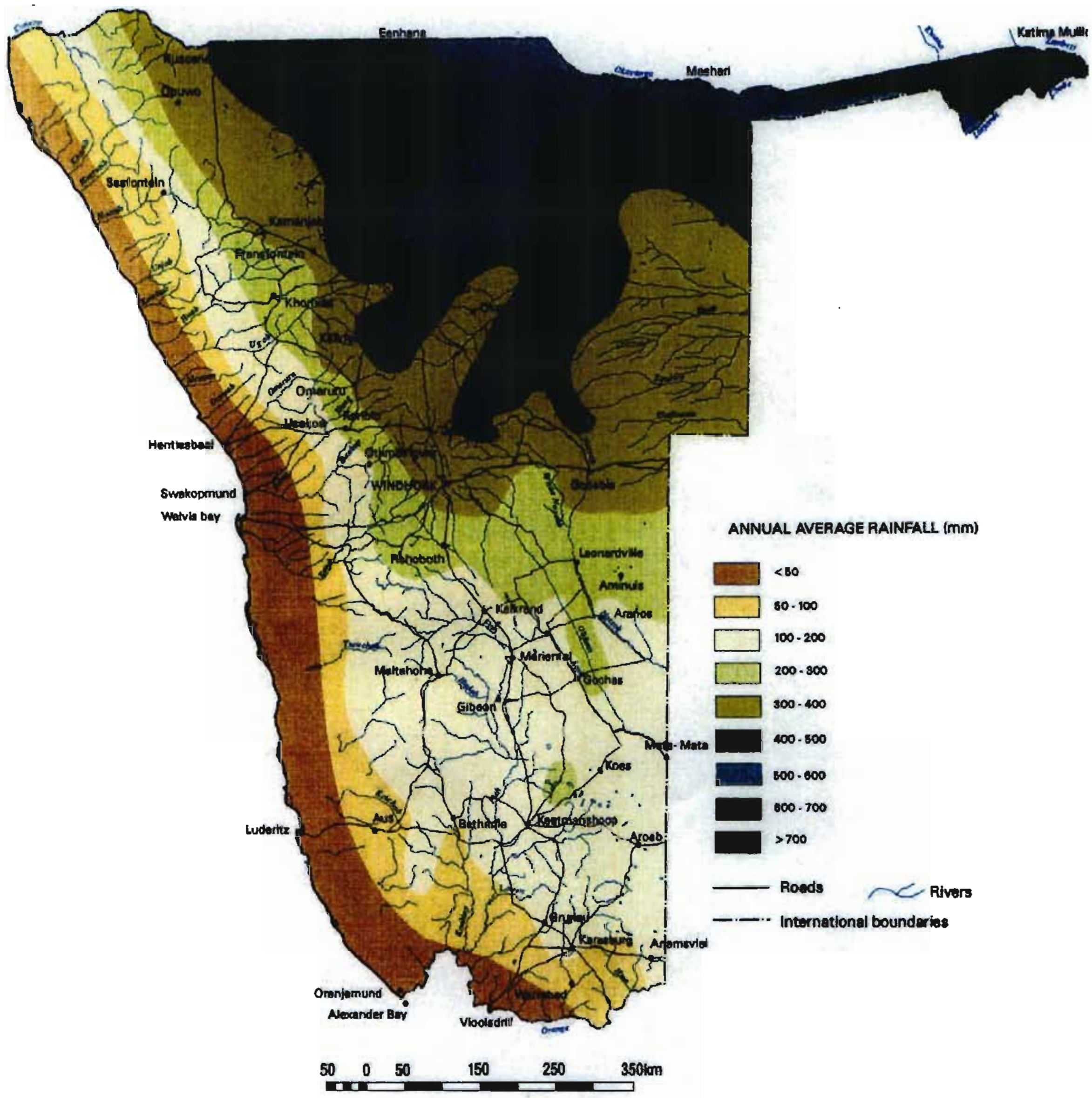

Figure 2. Distribution pattern of mean annual rainfall values across Namibia.

1.2.3. Economy

Mining, agriculture, fisheries and wildlife-based tourism form the four cornerstones of Namibia's economy (Lange et al., 1998). Although agriculture officially contributes only about eleven percent of GDP, of which about three percent comes from subsistence farming, animal and meat products constitute fifteen percent of export earnings and about seventy percent of the population is directly or indirectly dependent on the agricultural sector for their livelihood. About 75% of the total land area of Namibia is utilised for extensive livestock ranching and livestock farming contributes about 98 percent of the gross value of commercial agriculture (Lange et al., 1998).

1.2.4. Vegetation and Environment

Grassland or plains dotted with shrubs comprise most of Namibia's vegetation. Forest and scrub covers approximately fifteen percent of the country's area. In general, the northern and central regions are covered with savanna-type vegetation while the drier southern regions are typically open karroid shrub lands. Scoones (1994) points out that arid environments with highly variable climatic conditions exhibit the dynamics of non-equilibrium systems. He maintains that in these environments, range degradation does not pose as significant a dilemma as in wetter areas that have more consistent rainfall patterns and are thus inherently equilibrium systems. This opinion has as its foundation that since production potentials of livestock and forage are governed chiefly by rainfall conditions, livestock populations are kept in check and reduced through periodic drought seasons. Sandford (1994) concurs that in these non-equilibrium systems, livestock herbivory has only a limited effect on vegetation production potential. In contradiction to such assertions, Janson (1991) found that, in spite of the small population and low population density (about two people per square kilometre), there is evidence of areas where environmental degradation and desertification had occurred. Janson (1991) maintains that this is a direct result of misuse and abuse of the available resources. Land degradation is defined as a process that results in a continuous decline in production per hectare over time (Lange et al., 1998). In other words, damage ranging from detrimental vegetation changes to severe soil erosion manifests as a loss in production potential. This is evident particularly in the northern regions, as a result of a combination of population pressures, poverty and poor resource management practices. Janson (1991) notes that land degradation is particularly problematical in the agricultural sector, in both commercial and communal farming districts. The primary factors contributing towards this are over-stocking, overgrazing and bush encroachment. Bush encroachment is primarily occurring in the commercial farming areas, with the replacement of plants suitable for grazing with bush vegetation that is unsuitable as livestock fodder (Lange et al., 1998). Degradation in these regions is primarily a consequence of the fact that many commercial farmers look to maximise short-term profits and ignore environmental constraints in the process. That such attitudinal problems exist within the commercial farming communities has been recognised by the farmers themselves (Namibia, 1994). With agriculture being the primary form of land use, the contribution of this sector to the overall land degradation is of particular concern to environmentalists in Namibia. In addition, as the rangeland deteriorates, productivity is affected, with poor animal nutrition resulting in decreased slaughter weights and meat quality, with an associated drop in revenue. Milk productivity and hide quality are also negatively affected (Eckert et al., 1990).

Conditions are less than ideal for agriculture in Namibia (Eckert et al., 1990). Although it is Southern Africa's second largest region, it is also the driest and in many ways the most remote. The highly variable rainfall conditions, typically occurring over short and widely spaced time periods, induce vegetation growth periods with a high level of plant activity. With the cessation of the rainfall spell, moisture once again becomes a limiting factor, and plant activity declines. It is during this period that the influence of grazing plays a crucial role, since the rate of vegetation loss from the system after such a growth pulse is closely related to the amount of herbivory and the rate of natural decline, in the absence of veld fires (Pickup, 1994). This erratic forage supply, in conjunction with relatively constant demand for grazing, poses a challenge for effective and conservative pasture management.

Climatic and geographical conditions are of primary importance to Namibia's cattle farmers (Von Bach, 1990). As a result of the country's sparse and highly variable rainfall, the majority of the land that falls within the commercial farming districts is suitable only for stock farming. The southern regions are so dry as to be only capable of supporting small stock production, while the relatively higher rainfall in the central and northern parts of the country allow for extensive farming of small and large stock. The low rainfall limits the potential for crop production in Namibia, and the country has always been an importer of grains.

1.2.5. Namibia's beef industry

The beef industry plays an important role in Namibia's economy, with beef production forming the lifeline of the agricultural sector. The sale of red meat contributes over sixty percent of the gross value of the commercial agricultural sector (Von Bach and Van Zyl, 1990). Namibia has always been a net exporter of beef and mutton (Otto, 1990). Communal and commercial beef and mutton production constitute about 75 percent of Namibia's gross agricultural income, with about 96 percent of marketed livestock originating from the commercial sector (Lange et al., 1998). The amount of beef produced experiences wide fluctuations, with the environmental conditions having a marked effect in the form of characteristic periods of drought and erratic rainfall. The country's agricultural resources are fragile and sensitive to mismanagement as a result, and quickly demonstrate deterioration in the form of desertification, erosion and bush encroachment (Von Bach, 1990).

Beef production in Namibia is largely governed by geographical and climatic conditions. The relatively low and patchy forage productivity that characterises this region leads to grazing areas (paddocks) that are large and encompass considerable heterogeneity in vegetation. The eastern central region of the country records the highest beef production figures, followed by the central commercial areas around Windhoek (Namibia, 1994). Although cattle farming is practised in the drier southern region, small stock production (mainly sheep farming) pre-dominates in this region. Large stock farming is the norm in the central and northern regions, where the estimated carrying capacity is between 0.07 and 0.125 Livestock Equivalents (LSE) per hectare, where the ten main cattle-producing regions are located (See figure 3 below). Farmers of large livestock use extensive grazing practices, with natural pastures constituting the main feed resource, supplemented with salt, mineral and energy licks in the dry winter months (Namibian Meat Board, *pers. comm.*). Supplementary feeding is practised to a degree in the northern regions where vegetation is characteristically sourveld which decreases in palatability during the dry winter months. Sweetveld vegetation in the southern and central areas remains palatable during the dry season, so farmers do not implement supplementary feeding as a rule. The dominant breeds of cattle farmed in Namibia are the Afrikaner, Bonsmara, Brahman and Simmentaler.

Trade in meat occurs pre-dominantly in the form of live exports to South Africa and the European Union to a lesser extent, and Namibia's beef prices are determined according to export demand, mainly to South Africa. Internal slaughtering occurs only to meet the needs of the domestic market (Otto, 1990). Thus, beef producer prices are lagged weighted average prices obtained at South Africa's main abattoirs. Von Bach and Van Zyl (1990) applied multiple regression techniques to biological and time series data in their investigation of the supply response of beef sales in Namibia. Contrary to the accepted opinion that farmers are extremely price-responsive, they found that the producer's price of beef does not generally have a marked influence in the supply response; it is suggested that annual rainfall and current cattle numbers are the primary determinants of the annual number of cattle marketed.

In beef herds, it is usual practice to calve heifers only once they have reached three years of age (Preston and Willis, 1974). Fecundity is seen to increase to a maximum with age until cows reach approximately ten years, after which fecundity declines. Calving rates of 75 to 80 percent are considered to be attainable under conditions of adequate nutrition and good herd management. Commercial farmers use the slaughter-steer* production system, as feedlots are not financially viable due to the high transport costs and unreliability of grain production in this drought-prone country (Von Bach and Van Zyl, 1990). Cattle are usually slaughtered at about 20 months of age, with an average carcass mass of 225 kilograms. The factor converting carcass weight to live weight is 2.1. Lean beef from cattle between 20 and 36 months of age constitutes the category of greatest demand in the export market (Namibia, 1994). In fact, 54 percent of Namibia's beef production is Grade B beef, for which demand on the export market is high (Von Bach and Van Zyl, 1990).

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* Steers are sold from the system rather than being moved to feedlots and kept till they are older.

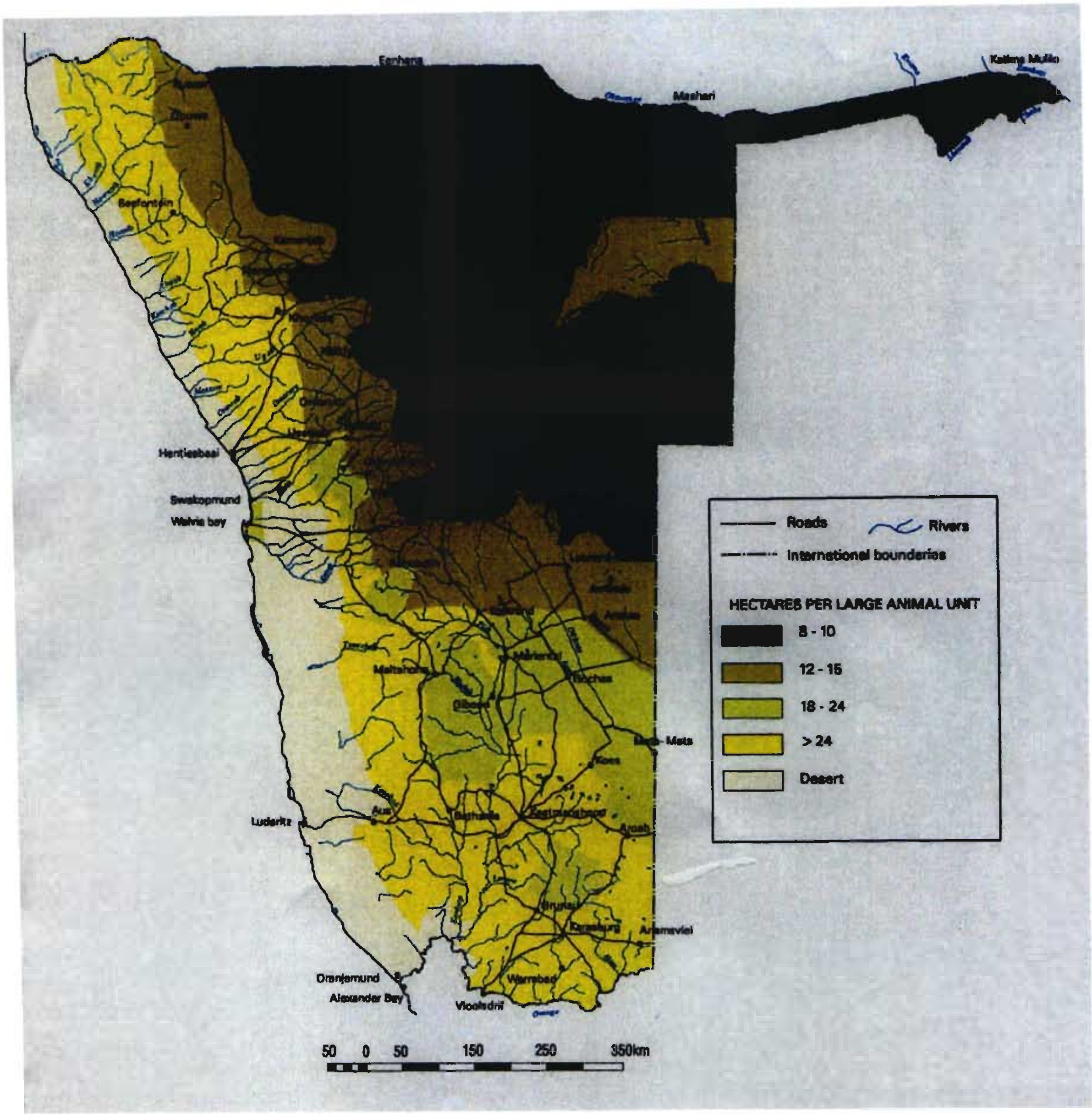

Figure 3. Distribution of recommended stocking rate zones for climatic regions across Namibia (Meat Board).

1.3. AIMS AND OBJECTIVES

In overview, this study aims to evaluate the performance of a set of management approaches in commercial beef operations in semi-arid regions exhibiting high rainfall variability. More specifically, the adaptation of an existing plant-herbivore model for the particular climatic, topographical and vegetative conditions characterising Namibia, and the incorporation of an economic component facilitates an evaluation of these management strategies in terms of various indices of comparison. This work seeks to contribute to, and clarify aspects of the ongoing debate in recent literature as to the effectiveness of implementing an adaptive stocking approach as opposed to a constant stocking level.

The inclusion of an economic component in the form of both a non-linear pricing structure and a dynamic feedback governing decision-making allows the performance of management strategies to be evaluated in terms of financial returns and variability of income as a measure of risk.

Summary of objectives

- To adapt an existing plant-herbivore model for Namibian climatic and vegetative conditions, and incorporate an economic component that includes a price classification system that captures the seasonal effects of price variability.
- To examine whether the implementation of adaptive stocking policies in response to climatic variation is successful in increasing revenue, reducing drought-related mortality and decreasing risk in the form of variability of income, by comparing the performance of adaptive stocking policies with a constant stocking rate approach.
- To investigate the effect of timing of offtake in response to anticipated drought conditions on herd performance and income.

- To develop and include a dynamic management approach in the model in order to examine the impact of assessing projected future income on current decision-making.

The work presented in this thesis has as its foundation the use of a mathematical modelling approach in investigating the behaviour and dynamics of a complex ecological system. The model aims to capture the dynamics of a rangeland agricultural system, constituted of vegetation dynamics and herbivore dynamics. Hence, a review of research carried out in this field and various models developed to emulate the dynamics of such systems is instructive; this review follows.

1.4. MODELS OF LIVESTOCK PRODUCTION SYSTEMS

1.4.1. Introduction

The use of mathematical modelling as a management tool has become common in agricultural production research. Denham and Spreen (1986) use the term "bioeconomic simulation" to characterise a mathematical description of an agricultural production system. Various approaches including simulation models, linear programming, dynamic programming and optimisation techniques have been used to varying degrees of complexity in order to meet a range of objectives. The objective of commercial agriculture is first and foremost the maximisation of animal production, and hence revenue generated, while ensuring the sustainability of rangeland resources in order to support such production. As such, the use of mathematical models to aid in decision-making has gained in popularity. Most models of agricultural systems focus on beef production efficiency, and the effects on this efficiency of factors such as management practises, environmental, nutritional and genetic changes, and economic fluctuations.

Ash and Stafford Smith (1996) suggest that "dynamic simulation models, which incorporate the spatial and temporal variability of rangelands, may be the best way of developing simple but useful management principles for setting stocking rates that are more appropriate than simplified regression relationships."

In modelling rangeland dynamics, there are a number of aspects that need to be considered and understood. Initially, the primary production of vegetation needs to be accounted for, so that plant growth and its responses to climatic influences and grazing can be simulated. Plant growth response describes the rate of increase of plant biomass as a function of plant density. A limiting factor affecting primary production and plant growth is water availability (Dye, 1983). Therefore, it is important to account explicitly for the effect of both daily rainfall and the long-term rainfall pattern when modelling vegetation dynamics in rangelands. Animal intake of available forage must be considered, as this affects plant growth, and determines the physical condition and reproductive capacity of the grazing herd. This intake is modelled in terms of functional response equations of the herbivore, which describe changes in the rate of forage intake by herbivores as a function of standing plant biomass. Herbivore numerical response is the rate of increase of the herbivore population as a function of standing plant biomass (Caughley, 1976). Thus herbivory i.e. the animals' response to the vegetation, can be modelled. The herbivore population also has an intrinsic response that accounts for the rate of increase of the herbivore population as a function of its existing density. Alternatively, the model needs to simulate the conversion of energy consumed in the form of vegetation into animal condition, which governs biological rates of the herd such as reproductive rate and mortality.

The level of detail that is required in a model is governed largely by the objectives in simulating the behaviour of a system. Detailed mechanistic models are better able to represent the complexity of a system and the intricacy of the causal relationships characterising a system. However, the more complex the system behaviour that is being reproduced in the form of a mathematical model, the greater the number of parameters that are involved (Pickup, 1995). The greater the degree of parameterisation, the more difficult it becomes to understand the relationships determining the various patterns of dynamic behaviour. Should the objectives of formulating the model require a great deal of detail, it should be noted that this is beneficial only when the information and data available about the system is of a high quality.

1.4.2. *Plant Production Models*

Although much research effort has focused on the development of models for the simulation of vegetation production and the implications for forage production of climatic variability and management regimes, researchers have yet to agree on the appropriate management response to the high rainfall variability characteristic of regions such as Namibia. It is useful to review some of these modelling approaches as a background to this study.

Existing plant production models vary widely in complexity. Wisiol (1984) reviews some of the earlier models, whose simplistic approach formulates regression equations of annual net primary production on rainfall-related measures. These models predict total annual vegetation biomass, taking into account historical yield values, shrub-herbage competition, current climatic conditions, soil type and annual water balance information (e.g. Sparrow et al., 1997).

Subsequent simulation models of plant production have been extended to include additional variables thought to play a significant role in vegetation growth, in addition to existing standing biomass. These include rainfall, efficiency of water use, soil nutrient availability, infiltration rates, geomorphology, soil-water balance, temperature effects and evapotranspiration (e.g. GRASP model, Stafford Smith et al., 1995, 1996). Models incorporating detailed photosynthesis processes, leaf geometry and variation in sward quality and composition (separation of swards into component parts such as stem and leaf) provide a mechanistic approach to grass-sward production (e.g. Thornley et al., 1994). Noy-Meir (1978) models biomass dynamics with plant growth rates influenced by plant respiration loss, light interception and the impact of herbivory, as well as a limit on the length of the growing season. Dye (1983) and Richardson and Hahn (1991) formulate growth relationships in terms of soil-moisture availability and water-use efficiency. This approach incorporates the effects of evapotranspiration, runoff and soil infiltration, as well as capturing the crucial influence, for arid and semi-arid rangelands, of temporal variability of rainfall.

Pickup (1995) uses a time sequence of remote-sensing and climatic data with the objective of predicting temporal variability in vegetation cover for given regimes of rainfall, landscape types and levels of herbivory. The model simulates herbage production using monthly rainfall and potential evapotranspiration, with loss of vegetation governed by grazing consumption and natural decay. The rainfall and evapotranspiration increase and deplete a moisture store respectively; the water use from this moisture store then governs potential plant production. Actual plant growth depends on water use as well as being a function of existing vegetation cover. An exponential decay function accounts for plant consumption, with consumption incorporating losses due to grazing, conversion to litter and biological decay. Grazing consumption is a function of the number of animals in the system, and is modelled using an asymptotic functional response in the form of an inverted exponential decay curve. The effects of radiation and temperature are not included in this model, except the effect of the latter on the potential evapotranspiration.

Olff et al. (in press) incorporates the critical factors of water availability and soil fertility in their model to simulate the influence of these factors on plant productivity, and explain the pattern of decline of plant quality with increasing water availability. The model assumes co-limitation of photosynthesis and growth by water and nutrients. Water availability is captured in a water-balance component, which includes input from rainfall, uptake by plants, run-off and evaporation. Standing plant biomass is a function of plant growth, plant turnover (due to decay) and herbivory.

1.4.3. Animal Production Models

Numerous animal production models have been developed to satisfy a variety of objectives in the study of beef production systems. Some consider the effect of stocking rate on vegetation production (Noy-Meir, 1978, Hacker et al., 1991) while others consider the financial impact of managerial decisions and link animal production to herd dynamics and economic performance (Cartwright et al., 1982; Denham et al., 1991; Foran and Stafford Smith, 1991; Gillard and Monypenny, 1990; Pratchett and Gardiner, 1991). Still others model population dynamics to assess animal production potential (Du Toit et al., 1995; Sanders and Cartwright, 1979a, 1979b). Stafford Smith (1996) outlines two motives underlying the drive to understand how animals use and impact on their forage resource:

- To predict the short-term economic outputs of different management strategies, and
- To predict the long-term impacts on the sustainability of production.

Early analytical models of plant-herbivore interactions were developed by Caughley (1976) and Noy-Meir (1978) among others. More recent models vary in complexity from simple feed models to detailed simulation of intricate plant and animal processes, and seek to take into account the non-linear relationship between grass production and herbivore production. Nutrient-based models relate an individual's nutrient requirements to the availability of the nutrient resource in the ecological system under consideration, which translates into the carrying capacity for the habitat. Various factors have been implemented as the constraining resource on this carrying capacity: these include factors such as plant dry-matter, radiation energy, soil moisture, precipitation and nitrogen (McLeod, 1997). The dynamic nature of recent animal production models facilitates effective handling of temporal variability in forage supply and stock numbers, which then allows for different management regimes and temporally-varying stocking rates to be modelled.

Senft et al. (1983) applied multiple regression analysis in formulating a series of predictive models of cattle spatial behaviour. Spatial models have been implemented to assess the impact of grazing on vegetation and patterns of variation in vegetation cover, by incorporating factors such as water distribution points, patterns of herd movement, distribution of animal activity and plant species gradients and composition. Using a spatial approach allows for the influence of the herbivore functional response on the patch dynamics of rangelands to be considered and diet selection and habitat choice of the animals to be incorporated (e.g. Pickup, 1994; Pickup and Bastin, 1997; Spalinger and Hobbs, 1992). Many of these models employ optimal foraging strategies, random-walk theory or diffusion analogies to predict these patterns of animal movement and their impact on rangeland productivity.

Sanders and Cartwright (1979a, 1979b) and Cartwright et al. (1982) describe a cattle production system simulation model, whose objective is to simulate the dynamic performance of a herd of cattle under given management scenarios, specified nutritional resources and a wide variety of climatic conditions. The objective of the modellers is to determine how a specific feed resource could best be utilised in a beef production system. The model allows for parameterisation for different breeds of cattle, and simulates animal and herd productivity for predicted levels of forage quality and availability. Nutrient consumption per individual per day is calculated as a function of forage quality and availability, as well as the individual's age, weight, body condition, genetic potential, relative degree of maturity and physiological condition. Forage availability and quality are specified on a monthly basis, in terms of dry matter digestibility, crude protein content and the weight of forage dry matter available per mature animal per day. Biological rates (growth, mortality, fecundity) and milk production are simulated as a function of genetic potential of the particular breed under investigation and the quantity and quality of feed intake. This animal production model is also used by Sullivan et al. (1981), linked with a stochastic, soil- and rainfall-driven plant growth model and a management decision component.

Denham et al. (1991) present a deterministic model of reproductive performance for beef production operations in North America. The primary objective of the model is to examine the influence of various biological and management variables on the annual production of calf groups within a specified time span. The authors consider gestation length, postpartum interval and conception rate as three biological variables that affect the reproductive efficiency of the herd. The length of the breeding season is governed by the herd manager, and is included in the model as a management variable. The annual calving percentage constitutes the response variable. Consideration of the influence of these three biological variables as separate entities rather than as an aggregated effect sets this particular model apart from other models of reproductive performance. This approach allows for a direct assessment of the individual effect that a change in a specific variable has on reproductive performance. The model's prediction of reproductive performance in cattle herds is shown to compare favourably with that recorded in field trials.

Foran and Stafford Smith (1991), Stafford Smith and Foran (1992) describe a simulation model for beef cattle production in arid regions. This dynamic herd and flock model, termed RANGEPACK Herd-Econ, tracks animal numbers and the herd's biological rates in age classes subject to regimes of buying and selling, which feed into an economics module that generates cash flow for the enterprise. The result is the simulation of the tactical decision-making of a livestock operation, which is used to compare various management approaches under sets of climatic conditions, specifically the effect of drought on the financial performance of the different strategies. Strategies compared include "high", "average" and "low" stocking policies, and the implementation of rapid de-stocking as a response to drought conditions. The options of no active de-stocking and de-stocking a percentage of the herd are compared as drought management tactics. Results from simulations show that both average and high stocking regimes have highly variable financial returns when compared with those produced by the "low stocking" approach which demonstrates consistency in returns. The implication is that a more conservative stocking regime brings fewer risks to cash flow, but lower aggregate returns over several decades. Other results show that de-stocking by 20 or 40 percent as soon as normal rainfall (judged according to long-term averages) has not fallen realises a higher economic return than the option of not de-stocking at all. It should be noted that these results are specific to the biological profile of the modelled area and the historical climate data applied in the model. The authors advocate de-stocking by 20 percent of the herd for a drought period of one year; however, for longer drought periods, de-stocking by 40 percent is the superior option. In addition, both de-stocking tactics demonstrate a lower variability of income than the option of not de-stocking. In a similar vein, we consider and compare strategies, in terms of income and variability, of maintaining a constant stocking rate in the face of drought conditions with so-called "panic sales" or pre-emptive sales, which are triggered by the rainfall not attaining a certain threshold percentage of long-term average rainfall by a specified date.

In an extension of the above study and relevant to our analyses, Foran and Stafford Smith (1991) present results of a comparison between a relatively high stocking rate/tracking strategy that fluctuates with forage availability, and a low, constant stocking strategy. The results show the former generating a higher cash return on average, but variance of return is much greater than that of the latter approach. In addition, they find that the tracking strategy requires rapid de-stocking in a dry year, while the constant stocking rate is relatively resilient to extreme rainfall conditions. They point out that the model used, while mimicking manager's tactics, does not have true biological feedbacks accounting for vegetation production and herd biological rates. The simulation model employed in our study seeks to incorporate both management decision-making and the underlying complexity of pasture growth and biological rates arising out of livestock-forage interactions.

RANGEPACK Herd-Econ (Stafford Smith and Foran, 1992) has been used by a number of researchers investigating various aspects of livestock production. Pratchett and Gardiner (1991) used RANGEPACK Herd-Econ to investigate the effect on financial returns of a reduction in stock numbers, a change in weaned status of the herd and an improvement in the genetic make-up of the breed. They show that implementation of these changes does not necessarily lead to a reduction in income. RANGEPACK Herd-Econ has also been used in representative studies (Buxton and Stafford Smith, 1996) using actual climatic data to investigate the economic impact of various drought management responses in Australia. Aspects addressed in this study include variability in financial returns, fluctuations in stock numbers and productivity, and overall profitability. Hatch and Stafford Smith (1997) applied RANGEPACK Herd-Econ with data from communal cattle herds in Kwa-Zulu Natal in order to investigate the impact on herd dynamics and the economic consequences of four management responses to an historical three-year drought period.

Comparisons of the total herd efficiency of individual breed types in terms of relative income per hectare using a simulation model indicates that mortality has a distinct influence on animal productivity, but the degree of influence differs for individual breeds (Du Toit et al, 1995). Fritz and Duncan (1994) performed a multifactor covariate analysis of total animal biomass, with rainfall as a covariate and soil nutrient availability as a factor, and found that both of these had statistically highly significant effects. Seré and Doppler (1980/81) also examined the influence of breed types in their simulation model HATSIM, designed to analyse the economics of large-scale beef production operations. Apart from the impact of different breeds on profitability, they investigated the impact of various grazing options (extensive in comparison with intensive grazing), price variability and improvements in the biological rates of the herd.

Modelling animal production using energy-balance relationships has proved useful in allowing the changes in animal condition to be monitored. This in turn provides an indication of the individual animal's reproductive capacity, survival probability and sub-cutaneous fat content. Many pasture-animal production models incorporate energy-balance sub-models to this end (e.g Fryxell, 1991; Illius and Gordon, 1998; Kahn and Spedding, 1984). Fryxell (1991) linked an energy-balance animal production model to a simple vegetation growth model to examine the benefits, or disadvantages, of aggregation by large herbivores.

Hacker et al. (1991) implemented a simulation modelling approach in evaluating alternative management strategies over extended time periods for the arid regions of Western Australia. They present a generalised model termed IMAGES comprising sub-components capturing the dynamics of the soil-water-animal system. These sub-components include a soil-water balance sub-model, three vegetation sub-models, an animal intake sub-model and an animal production sub-model. The initial condition of the vegetation is considered as the starting point of plant growth and is formulated as a function of past grazing history and natural decay.

1.4.4. Composite, Management and Stocking Rate Models

Dynamic simulation models offer useful insights into the effects of implementing a range of alternative production strategies for complex agricultural systems (Richardson and Hahn, 1991). Ecological modelling approaches have given rise to much work aimed at determining stocking rates that are both economically optimal and biologically sustainable, and predicting performance levels of cattle herds under a range of stocking regimes and climatic conditions (Danckwertz and King, 1984; Bransby, 1985; Brockett et al., 1982; Carew, 1976; Hearne and Buchan, 1990). These models typically link rainfall with forage production and veld condition: herd population dynamics are then a function of one or both of these, often with management decisions as a contributing influence. While the relationships linking gain per animal to stocking rate differ, with some taking an exponential form and others being linear, a common feature of all these productivity versus stocking rate models is the decline of productivity per animal with increasing stocking rate. Central to all these types of models is that productivity per unit area is assumed to be a curvilinear function of stocking rate. As stocking rate increases, so does productivity per unit area until a threshold stocking level is reached after which productivity per unit area declines with increasing stocking rate. The Jones and Sandland (1974) production model is frequently cited and forms the foundation for many similar models where animal productivity is a linear function of stocking rate. Jones and Sandland (1974) hold that this linear relation provides a better fit to empirical data than previous exponential models, although Stafford Smith and Foran (1991) suggest that this model does not adequately cope with spatial and temporal variability in its current formulation. More recent models differ in that maximum productivity per hectare is not necessarily equated with optimum stocking rate (McLeod, 1997).

Research has been conducted for both communal and commercial livestock operations. Hearne and Uys (1985) formulated a dynamic, non-linear model for a subsistence pastoral system, incorporating aspects of fodder production, herd dynamics and economic returns with a view to determining an optimal stocking density coupled with an offtake strategy that maximises revenue from the commercial sale of stock. Bransby (1984) developed a regression model that related daily livemass gain per animal and daily livemass gain per hectare to stocking rate and rainfall. By considering the rate at which daily livemass gain per hectare is a maximum, he calculated values for maximum stocking rates, and showed that, for increasing rainfall values, daily livemass gain per hectare increased with maximum stocking rates up to a threshold level, after which it began decreasing. However, he showed that, for a wide range of stocking rates, the value of daily livemass gain per hectare reaches 90 percent of the maximum value which corresponds to a given maximum stocking rate. It is intuitive that average daily gain per individual will be constrained at some critical stocking rate value, and will begin to decline once this threshold value is exceeded, as quantity limitation begins to influence herbivory. It is not only the limitation of quantity that plays a role however; at lower stocking rates, the animal also has greater freedom to select forage of higher quality (Brockett et al., 1982). Bransby (1985) points out that models relating profit to stocking rate should take variation in annual rainfall into account, since the unpredictability of rainfall in a forthcoming season results in managers having to make adjustments to their herd size at short notice. He details a model relating profit to stocking rate and annual rainfall, and uses this to determine the stocking rate that yields maximum profit for a given annual rainfall value.

Richardson and Hahn (1991) linked a number of sub-models in a temporal, dynamic model to predict the effects of rainfall, stocking rates and management policies on herbage availability, body mass of animals, herd composition and herd output. They investigate the impact that the timing of management decisions has on the subsequent herd performance and veld condition. The vegetation sub-component uses Dye's (1983) soil moisture and grass growth models; it comprises rainfall inputs, drainage and soil moisture variation, changes in vegetation biomass due to decay, grazing effects in the form of foliage depletion, and evapotranspiration. The animal production component incorporates digestibility and ability to metabolise the diet, amount of dry matter* intake as a function of forage availability and digestive capacity, selectivity in grazing, and energy balance equations. Management options that can be exercised include variation in weaning age, sales strategies, timing of offtake, stocking rate changes in response to rainfall conditions and the proportion of cows in the herd.

Stafford Smith et al. (1995, 1996) have developed a number of models as an ongoing collaborative project with input from various stake-holders in Australia, including livestock producers, governmental agencies and researchers. The objective of "Drought Plan", as it is termed, is to assist producers in developing economically-viable drought management strategies to cope with climatic variability, market fluctuations and changes in land productivity, while increasing animal production efficiency and sustaining the land resource. These models are then linked in a hierarchical approach to constitute an integrated simulation tool for livestock enterprises with their overlying financial implications. The result is the composite model, RISKHerd, whose outputs reflect management strategies in terms of both financial implications and sustainability of range condition. Simulations show that financially-optimal stocking targets can be defined for various stocking rate options and management strategies.

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* Forage containing zero percent moisture.

The influences of stocking rate, rainfall variability and forage production on economic performance and economic risk have been examined using a variety of modelling approaches. Gillard and Monypenny (1990) determine pasture availability, and hence liveweight gain, reproduction and mortality, using annual rainfall from 20-year historical sequences as the only input for a spreadsheet model of herd dynamics. The model is used to address questions of rangeland degradation and economic risk and to provide decision support for stocking responses in drought conditions. Results indicate that the best option for a manager faced with drought is de-stocking as opposed to supplementary feeding.

Scenarios simulating risk arising from rainfall variability, stocking rate and production levels, and price fluctuations have been implemented in various dynamic optimisation models, with the objective of obtaining optimal management and marketing policies for livestock operations (e.g. Patrick et al., 1985; Rodriguez and Taylor, 1988; Garoian et al., 1990; Carande et al., 1995; Schroeder and Featherstone, 1990; Uys, 1986). Patrick et al. (1985) apply a dynamic programming approach that allows for alternative optimal responses with a range of stocking rate options as opposed to a unique solution – this permits an individual manager's risk preference in terms of the current climatic and price situations to be taken into account. Rainfall input for the model is stochastic and is simulated using a Gamma-distributed rainfall generator. Timing of offtake is governed by the type of risk scenario chosen – this in turn governs stocking rate levels and variability. A result relevant to this study, and intuitively sound, is reported in Patrick et al. (1985) – early sales of livestock are shown to be important in limiting financial losses in a scenario where rainfall is below average and stocking rates are moderate to high. In addition, favourable rainfall conditions exert a greater influence on the timing of sales than does the current market price. However, the influence of price level becomes more marked under adverse rainfall conditions at low and moderate stocking rates.

Garoian et al. (1990) propose that economic benefits and reduced risk might be achieved through implementation of flexible marketing policies in conjunction with smaller breeding herds. They developed a dynamic programming model that incorporates cattle prices and range condition (in terms of forage available) as stochastic state variables and stock inventory as a deterministic state variable. The governing recursive equation is a function of inventory, cattle price and forage availability. The objective of the model is to maximise the expected present value of net returns over a ten-year period. Their results suggest that the adoption of flexible management strategies, regardless of stocking level, will provide improved net returns. A dynamic programming approach applied by Rodriguez and Taylor (1988) shows that flexible stocking policies within a grazing season to trace seasonal trends in forage production increased the economic profitability of the system. In addition, they found that postponement of sales, and/or increasing stock levels increased the value of the marketing risk, measured as the difference between net present value (NPV) and expected net present value (E[NPV]).

The volatile markets that characterise the cattle industry give rise to models whose objective is to analyse the effects of management and marketing options in an attempt to quantify economic risks and guide managers in their decision-making. Uys (1986) examines the cyclical nature of the South African livestock industry using a system dynamics model that incorporates the economic aspect of expected prices, price fluctuation, supply and demand and inventory flow: these are coupled with a herd dynamics sub-model. The model is formulated in terms of first-order differential equations that include first-order delay terms. Schroeder and Featherstone (1990) apply a dynamic programming approach to a cow-calf production system. In this type of system, calves can be marketed at various time periods – herein lies an important management option, since price uncertainty is a significant factor for retained calves, as is production uncertainty. The model incorporates discrete random events and continuous choice variables, i.e. a dynamic decision process as opposed to a static one. The model is temporally finite and stochastic, and explores optimal calf retention decisions and marketing strategies that reduce the production system's vulnerability to adverse market price levels. Price variation is included by associating a distribution of prices to each price realisation. Future cattle price expectations are used to determine the value of retained calves.

The studies undertaken in the literature reviewed above fail to provide consensus on the question of a management approach that is successful in optimising returns and reducing income risk from commercial livestock production while ensuring sustainability of forage resources in variable climates. This provides the impetus for this study, to seek some clarification on which management options should be chosen to meet these objectives.

Before presenting the analysis, some key concepts underlying aspects of this work are discussed in Chapter Two.

CHAPTER TWO

MODELLING LIVESTOCK PRODUCTION SYSTEMS IN ARID AND SEMI-ARID RANGELANDS: SOME KEY CONCEPTS

2.1. INTRODUCTION

Throughout Southern Africa, climatic conditions are such that rainfall distribution, both within and between years, is highly variable and hence unpredictable. This typically low and erratic moisture supply, along with temperature extremes, thus constitutes a major factor limiting primary production and hence agricultural productivity in semi-arid and arid rangelands. In fact, water and nutrient availability are considered to be the main factors limiting plant growth in semi-arid environments (Dye, 1983). In years of limited rainfall, plant production is negatively affected; however, seasons of favourable rainfall result in abundant herbage availability.

The challenge for managers of commercial livestock production systems, then, is to establish a balance between the optimal exploitation of these periods of abundance, while somehow minimising risk of mortality in the face of unpredicted drought conditions. Barnes and McNeill (1978) identify periods of drought conditions as "critical" or "limiting" seasons, and suggest that managers stock at a rate that ensures adequate fodder availability during seasons of low plant production. Dye (1983) concurs that managers should stock to match the most limiting year, and Danckwerts and King (1984) note that conservative stocking rates improve the farmer's ability to tolerate drought conditions without adversely affecting productivity. Obviously, this conservative approach precludes full advantage of favourable climatic conditions and associated abundant plant growth being realised.

The objective of any livestock operation should be sustainable production. The options for managers of such operations in variable climates range from matching stocking rates to forage supply on the one hand, to operating at low stocking rates that are resilient to rainfall variability in all but the most extreme conditions on the other. The former, while accompanied by an increased risk factor, offers the potential for greater returns in favourable years while minimising losses under drought conditions. The latter provides a constant and reliable level of production, and risk is reduced; however, the opportunity to increase production and hence revenue in years of forage abundance is lost. The ideal scenario is to establish a balance between these two approaches: according to Stafford Smith (1996), this balance is governed by vegetation resilience* to short-term overgrazing, the farmer's economic reserves and risk preference, and climatic variability.

Buxton and Stafford Smith (1996) describe the need for models of livestock production systems that incorporate:

- The manner in which pasture quantity and quality respond to rainfall and herbivory,
- The influence of forage availability and seasonal variability on livestock performance and biological rates of the herd, and
- The impact of livestock performance, management strategy and market variability on overall economic performance of the enterprise.

Indeed, a valid economic analysis of a livestock enterprise must have as its foundation a comprehensive and accurate account of the biology of the system (Levine and Hohenboken, 1982).

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* Resilience is a measure of the extent to which an ecological system can change in response to external influences but can still return to its original state once conditions revert to their previous status (Trollope et al., 1990).

2.2. THE IMPORTANCE OF STOCKING RATE

As a management factor, stocking rate can be considered to be a fundamental influence affecting rangeland productivity and stability. In fact, it can be viewed as the most important management variable that is under the control of the livestock farmer, since it has a primary influence on animal production and range condition, productivity and stability. In addition, the severity of the effect of drought conditions on cattle depends largely on the stocking rate. So management of herd size is a trade-off between having sufficient stock in favourable rainfall seasons to make optimal use of available forage and having too many in drought years leading to high stock mortality and detrimental effects on long-term pasture production (Gillard and Monypenny, 1990). An optimum stocking rate is considered to have been attained when maximum productivity per unit area, or maximum productivity per head, or a combination of these two measures, is achieved; ideally, the concept of a "correct" stocking rate should encompass both optimal production *and* protection of the forage resource (Stafford Smith, 1996).

Stocking rate strategies are driven by the overall pasture productivity, through the forage supply and composition and its temporal variability. Vegetation production translates into the concept of carrying capacity of the rangeland. Assigning a carrying capacity to a system implies that there exists an equilibrium plant-herbivore space within which a defined level of sustainable livestock production may be anticipated (Tainton et al., 1996). Caughley (1979) proposed a partitioning of the concepts of carrying capacity into two categories: the equilibrium imposed by sustainable harvesting of herbivore populations being termed "economic carrying capacity", while "ecological" carrying capacity refers to the equilibrium that results from the unmanipulated interaction of plants and herbivores. Danckwerts (1982) defines carrying capacity as "the potential of an area to support livestock through grazing and/or browsing and/or fodder production over an extended number of years without deterioration to the overall ecosystem".

Carrying capacity has been quantified using a number of different approaches. Units of measure commonly used are animal units per unit area, energy consumption per unit area or biomass per unit area. One animal unit (or livestock equivalent) is that biomass of ungulate consuming the same amount of energy as an average steer of mass *A*, where *A* is taken to be 450kg. Then the number of animal units that an animal of mass *M* constitutes is calculated as $\frac{M^{0.75}}{A^{0.75}}$ and $A^{0.75}$ defines the metabolic liveweight of the animal (Tainton, 1981). This metabolic liveweight is used extensively to evaluate biological and economic components of animal production agriculture.

By estimating indices of usable primary production in the herbaceous layer of vegetation, agriculturalists often express carrying capacity for domestic livestock as the number of hectare required to support one animal unit (Mentis, 1977). McLeod (1997) defines carrying capacity in plant-herbivore systems as that equilibrium density that can be attained by a herbivore population. Fluctuations in carrying capacity with rainfall governs the need to buy or sell stock, and may alter average stocking rates (Campbell et al., 2000b). Conservative stocking policies typically result in veld condition being improved or at least maintained; in contrast, overstocking leads to severe range degradation (O'Reagain and Turner, 1992). An assessment of veld condition is crucial to both researchers and farmers alike, as it exerts a profound influence on the profitability per hectare of veld (Danckwerts and King, 1984). In order to facilitate the improvement, or at least the maintenance of veld condition, it is necessary for livestock farmers to make an assessment of the range of stocking rates that can support sustainable and profitable production. In order to do this, they need to consider the "grazing capacity" of the available forage resources. Danckwerts (1982) defines grazing capacity as describing "the productivity of the grazable portion of a unit of vegetation, and is the number of animal units that can be maintained per unit area of land in order to achieve maximised animal production per unit input under consideration, but does not permit soil erosion or changes in the botanical composition that reduce the potential of the vegetation to produce animal products". This definition revises previous definitions and allows for the grazing capacity to fluctuate within and between climatic seasons and for vegetation and/or soil deterioration. By defining grazing capacity in this way, Danckwerts (1982) takes into account the influences of veld condition, forage on offer and annual rainfall on grazing capacity. He suggests that grazing capacity should be expressed in units of animal units per hectare or grazing days per hectare, as both of these increase with increasing grazing capacity and are linearly related to the number of animals on an area of land.

Studies in Queensland, Australia, have indicated that in the short term, increasing the stocking rate on a farm improves profits, but that this falls off once the effects of range degradation begin to negatively impact production (Stafford Smith, 1996). For commercial livestock farmers, changes in the annual offtake by mass per hectare is often the best indicator of range degradation and corresponding loss of productivity. Ash and Stafford Smith (1996) contend that many of the stocking rate experiments that have been conducted in the past have been performed on production systems and land that is being intensively managed. They observe that the temporal and spatial variability of extensive rangeland systems limit the practical application of experimental stocking rate experiments to these systems. Specifically, limiting factors include:

- Inter-annual and seasonal fluctuation in forage production, vegetation composition and quality;
- Long-term vegetation changes;

- Temporal and spatial patterns of diet selection by grazing animals in complex vegetation; and
- Impacts on animal production parameters other than growth of meat or wool (for example, reproduction, mortality etc)

Management decisions are not primarily based on biological responses; the economic effect of a decision is usually the first consideration of a manager (Denham et al, 1991). Rangeland degradation is the long-term consequence of prolonged overgrazing. Stafford Smith and Foran (1992) suggest that implementing low stocking rates early in a drought situation allows for the maintenance of a forage reserve that can sustain production in subsequent drought years: they suggest that this should be a primary management objective. Managers often ignore the likelihood of damage to the veld in making their stocking decisions, since such effects often only become apparent after years of overgrazing. Hence there is a tendency to stock heavily to increase the profits obtainable from a given area. Researchers considering relationships between stocking rate and animal production seem to agree that there exists some critical threshold stocking rate for a given region, below which gain per head stays constant, and decreases as the stocking rate increases above this threshold value (Ash and Stafford Smith, 1996). Results presented by Hacker et al. (1991) are in keeping with this consensus – they find that production per head is severely reduced at higher stocking rates, particularly during low rainfall years.

Application of theoretical linear stocking rate models (e.g. Jones and Sandland, 1974) to extensively managed rangeland systems typically gives rise to overstocking, as managers experience the benefit of short to medium term profits. The response of animal production to increasing stocking rate is relatively flat, so with higher stocking rates, maximum gains per hectare can be realised (Ash and

Stafford Smith, 1996). However, these stocking rates are not sustainable in the long term, and the consequences are normally severe, with degradation and bush encroachment leading to diminishing production potential of the system, and corresponding decreased profitability. Carew (1976) found a close correlation between stocking rate and live-mass gains by steers grazing veld. This infers that live-mass gains and profits per unit area are markedly affected by the chosen stocking rate.

The perception of many managers appears to be that stocking heavily will increase beef output and consequently improve economic returns. There is general agreement that there exists a threshold stocking rate, below which animal production per head remains constant. Above this critical stocking rate, animal production per hectare declines quadratically with increasing stocking rate (Ash and Stafford Smith, 1996). The implication of this consensus is that a range of stocking rates may be applied without resulting in range degradation, provided the critical stocking rate for a particular vegetation type is not exceeded (O'Reagain and Turner, 1992). A single optimum stocking rate, as used in the linear Jones-Sandland model (1974), is not conducive in rangelands typified with high interannual climatic variability and fluctuating stock numbers. In addition, rangelands exhibit spatial heterogeneity in vegetation, which is not a factor in the small, relatively homogenous paddocks for which the Jones-Sandland relationship was formulated (Stafford Smith, 1996). In trials at Matopos Research Station in Zimbabwe, Carew (1976) compared returns from both a lighter stocking rate and one that yielded maximum output per unit area, and found the former approach resulted in higher profits per unit area than the latter. Danckwerts and King (1984) found similar results when they considered the profit obtainable from livemass gain of steers in an existing livestock operation. In addition, they found that maximum income per hectare was lower and occurred at a lighter stocking rate in years of low rainfall than that corresponding to high rainfall years. Stafford Smith and

Foran (1991) showed that a management policy that is extremely averse to drought risk and hence selects a below-average stocking policy returns a poorer economic performance than both a high stocking- and average stocking option. However, returns are shown to be less erratic for the former and the strategy seldom places managers in a position where a crisis is faced and crucial decisions are required to avert disaster.

It has been observed that with increasing stocking rates, production per hectare increases to a certain level, while individual animal performance deteriorates. The implication is that total animal production is optimised at moderate stocking rates (O'Reagain and Turner, 1992). Danckwerts and King (1984) point out that livestock subjected to heavy stocking rates experience a reduction in performance that can be ascribed to diminished herbage availability, as well as being more susceptible to mortality in the face of drought conditions. Barnes and McNeill (1978) are of the opinion that the effect of stocking rate on animal production is secondary to the effect of stocking *pressure*, the latter being the amount of herbage on offer per animal unit. Another theory holds that herd dynamics are most influenced by rainfall conditions that reach high or low extremes. In contrast, it is stocking density that exerts the largest influence on animal dynamics in years of average rainfall conditions (Perrings and Stern, 2000). Brockett et al. (1982) found that in years of favourable rainfall conditions, average daily gain of individuals was less sensitive to the influence of stocking rate. They also observe that average daily gain is lower in wetter years, and surmise that this is as a result of accumulated vegetation from the previous season diminishing in nutrient quality. The primary objective of livestock managers is the achievement of sustainable and profitable production. Foran and Stafford Smith (1991) describe a sustainable livestock production system as one that can maintain high biological rates such as reproductive rates and rates of weight gain, and low mortality rates for periods in excess of 20 years. They hold that the consistency of these rates, as well as their resilience during unfavourable seasons, govern medium and long-term profitability. The biological rates attained by the herd are governed chiefly by the medium- and long-term feedback between rainfall and stocking rate, which in turn influences changes in forage availability. Indeed, the influence of previous season's rainfall typically has a greater influence on the herd's biological rates than the current season's rainfall, while the sequence of rainfall seasons can have a marked effect (for example, one-year drought periods tend to have less of an impact on productivity than two consecutive dry seasons). (Buxton and Stafford Smith, 1996).

2.3. THE INFLUENCE OF RISK ON DECISION-MAKING

Risk in a commercial beef operation arises in various forms. Risk analyses conducted for livestock production systems have, almost exclusively, used price fluctuations and yield variability as a measure of risk (Patrick et al., 1985). Market conditions and price variation, not necessarily correlated with climate, obviously have a marked effect on the economic performance of such an operation, and managers face the risk of price collapse – this makes timing of offtake highly relevant. Surveys conducted by Patrick et al. (1985) amongst livestock managers in the United States show livestock prices as the most important source of net-return variability in their operations. Climatic conditions also rank highly as a fundamental source of variability. Risk associated with climatic influences, particularly in arid and semi-arid regions, includes the uncertainty of the duration of drought conditions, which can lead to stock mortality. Another "climatic" risk is taken when attempting to combat mortality by de-stocking; the manager sells pre-emptively in the expectation of continued drought conditions, only to experience favourable rainfall and hence a loss in potential production. One option is not to sell pre-emptively in the face of an anticipated drought, and adopt a "wait-and-see" attitude. Should drought conditions then materialise, with resultant loss of stock condition, a dilemma arises when the manager foresees that certain individuals are at risk of mortality. Does he then sell at a lower return or does he gamble that the animal will survive until forage availability improves? Finally, maintaining high stocking rates in order to ensure higher returns carries with it the risk of associated land degradation, which inevitably will negatively affect productivity in the long term. This "more cattle – more money" syndrome ignores two vital concepts: rangeland degradation and the manager's attitude to risk (Foran and Stafford Smith, 1991). Managers of livestock operations can adopt attitudes that are "risk-averse", "risk-neutral" or "risk-inclined"; the impact of such management approaches is examined by Foran and Stafford Smith (1991).

Certain management responses and observations in the face of drought have been found to curtail mortality and loss of revenue. These include:

- Timeous reduction in livestock numbers (involving some guesswork).
- Maintaining the breeding herd as far as possible
- Sale of older steers and cull animals before any other category. (Cull animals are cows with poor production records, weaner heifers and steers.)
- Young stock are more prone to lose condition and starve during food shortages than older animals, hence one option is to remove these first when de-stocking. An added advantage of this approach is that maintaining a higher than normal ratio of mature cows to heifers will ensure improved post-drought production since cows tend to have higher fecundity rates than heifers facing their first or second pregnancy. However, there is a trade-off in choosing to cull younger animals, since younger animals have lower maintenance requirements and tend to recover condition more rapidly than older animals in the post-drought period, hence increasing potential revenue from sales of these animals.

(Gertenbach *pers. comm.*)

The extensive management practises of most commercial livestock operations in Namibia imply that food supply is not deterministic. Rather, range forage availability is dependent on stochastic environmental conditions, primarily rainfall. In determining optimal management policies, it is important to account for this source of uncertainty. Price uncertainty also plays a role, since in the face of prevailing low stock prices, managers may retain stock for a period of time in the expectation that market conditions will improve. The gamble here is that prices will remain depressed, while saleable animals could lose condition as winter approaches and veld condition declines. While periods of greatest demand coincide with the highest market prices, high prices are only generated for animals in prime condition (Abdullahi and Jahnke, 1991). So the timing of offtake becomes critical to the profitability of the enterprise. Balancing expected weight gain or loss with potential economic returns involves some educated guesswork on the part of the farmer – application of this model in a dynamic market framework (Chapter Four) aims to quantify the decision process and analyse the economic consequences thereof.

2.4. LIVESTOCK-FORAGE INTERACTIONS IN RANGELAND SYSTEMS

The productivity of rangelands is governed by the balance between palatable and unpalatable vegetation species available to herbivores. In semi-arid and arid systems, where the process of species change is event-driven, increasing grazing pressure triggers a reduction in the proportion of palatable to unpalatable plants (Perrings and Walker, 1997). In other words, changes in grazing pressure can effect transitions between equilibrium states. In these systems, where extreme climatic conditions are common, management of rangelands needs to be opportunistic and event-driven itself.

A typical response to a drought situation sees animal numbers decline naturally, chiefly due to mortality, as a result of diminishing pasture production. In a situation where a drought year follows a period of favourable or average climatic conditions, rainfall in the current year only has a moderate effect on the herd. Should prolonged drought conditions be experienced in subsequent years, this exerts a strong influence on herd dynamics as the cumulative effects of drought work to lower the carrying capacity of the rangeland (Perrings and Stern, 2000). Tainton et al. (1996) concur that single-year droughts in arid and semi-arid systems seldom affect population numbers, although animal condition suffers: it is the multi-year drought cycles that precipitate a decline in herd size. Once rainfall conditions improve, the vegetation is quick to recover; however, cattle productivity is slower to respond in cases where herd losses have been substantial, with population numbers taking time to regain pre-drought levels. This lagged response time between plant production levels and cattle population numbers limits the extent to which managers can maximise available resource usage. In fact, the lagged response inherent in livestock production often means that the results of management decisions are not apparent for a number of years subsequent to implementation of the decision. This lagged response in vegetation production can also be observed following instances of overstocking, although feedbacks from the effects of damage are slow to occur and often difficult to isolate from the climate-driven production variability. Even once animal numbers have been reduced subsequent to a period of overstocking, rangeland deterioration continues to occur due to a decline in the net primary productivity of the land. The reduction of plant density can result in increased run-off and corresponding decrease in infiltration. Higher nutrient loss occurs as a consequence (Wilcox, 1963).

Modelling forage intake of herbivores allows for an estimation of animal condition and biological rates of the herd. Models involving estimation of animal feed intake commonly include a measure of animal size and forage quality. Accurate prediction of intake and its nutritive value is critical in models of animal production, since livestock performance is governed chiefly by the nutritional status of the animals. A measure of intake often used is one of dry matter (DM) intake (e.g Kahn and Spedding, 1984; Sanders and Cartwright, 1979a, 1979b). Kahn and Spedding (1984) used a dynamic simulation model incorporating DM intake equations in order to predict weight changes in growing grazing steers. Their results show a close correlation between measured weights and those predicted by the model. Cartwright et al. (1982) suggest quantifying the biological efficiency of a grazing herd by construction of an index comparing the total units of dry matter consumed by the herd per unit liveweight sold from the system.

2.5. AN ALTERNATIVE APPROACH TO THE STOCKING RATE DILEMMA

Rangeland production is a dynamic process in which biological efficiency and expected income are governed by fluctuations in rainfall and price uncertainty respectively. The practise of farm managers attempting to mirror changing patterns of pasture productivity, largely as a result of climatic variability, has become widely referred to as "tracking". Scoones (1994) describes the achievement of effective tracking by de-stocking animals through sales during drought and restocking when fodder is available after the drought. Behnke and Kerven (1994) define biological tracking as the timeous removal and restocking of livestock in response to fluctuating levels of available herbage. In other words, biological tracking constitutes an opportunistic management strategy that endeavours to follow the effects of environmental fluctuations by adjusting stock levels and distribution so as to maintain equilibrium between stock numbers and available feed resources. Thus, managers attempt to capitalise by maximising resource use during favourable climatic conditions, while minimising economic losses through stock mortality in drought years.

Stafford Smith and Foran (1991) suggest that managers can either benefit from variability in the system by exploiting its opportunities (an approach which is often risky), or they can seek to minimise the effect of variability by taking a more conservative approach. Patrick et al (1985) report that implementing flexible marketing strategies under a high stocking regime reduces variability in net returns, particularly when rainfall and price levels are below average. Implementation of flexible marketing strategies allows for more efficient use of the forage resource and the potential ability to capture seasonal price variations, particularly in arid environments characterised by highly variable rainfall (Garoian et al., 1990). Behnke and Kerven (1994) propose that management approaches should include a combination of tracking and buffering strategies. They describe economic buffering as the buffering of environmental fluctuations by shielding incomes from the extremes of climatological and biological variations. In other words, economic buffering involves minimising the coefficients of variation of the value of product output, so dampening the effects of environmental variability on income.

The issue of whether to practise an opportunistic management strategy such as tracking as opposed to the approach of maintaining a conservative, constant stocking rate, has proved contentious and has been hotly debated in recent literature. (Behnke and Kerven, 1994; Campbell et al., 2000a; Foran and Stafford Smith, 1991; Illius et al., 1998; Sandford, 1994; Scoones, 1994; Toulmin, 1994). The latter is considered by some to be an inappropriate management strategy for rangeland systems, in that the inter- and intra-annual variability that characterise these systems effects variation in plant production and corresponding carrying capacity. Behnke and Kerven (1994) contend that in arid environments that experience extreme variability in rainfall, maintaining a stocking rate that is low enough to ensure that non-occurrence of forage shortfalls would be uneconomic, although this risk-averse strategy does have as an advantage the reduction in drought-related stock losses. It is their opinion that "the environmental benefits of conservative stocking regimes are as dubious as their purported economic benefits". Rather, they suggest that managers should be flexible enough in their stocking approach that they are able to adapt rapidly in response to unpredictable environmental fluctuations, in order to minimise the economic and environmental consequences thereof. A caveat is added to this opinion, however: that in order for beef producers to accept and practise these proposed flexible stocking strategies, these strategies must be seen to be economically advantageous as well as environmentally beneficial. Patrick et al. (1985) support this assertion in stating that "under rainfall variability, flexible rules of management will have a positive effect in the economic sustainability of the enterprise and the biological sustainability of rangelands". Illius et al. (1998) concur that adapting stocking rates in accordance with environmental fluctuations could be successful in limiting drought-induced mortality and improving levels of production.

Arid and semi-arid environments are generally accepted to constitute dynamic, non-equilibrium ecologies, separated from equilibrium systems by the contour line of 30 percent co-efficient of variation of annual rainfall (Sandford, 1994). Scoones (1994) addresses the issue of flexible stocking strategies in these arid and semi-arid ecosystems, and summarises the following as an argument in favour thereof:

- External factors such as drought are the primary determinant of livestock numbers and vegetation status, and therefore herbivory has a limited influence on long-term vegetation productivity. So, in such systems, opportunistic strategies favour the protection and conservation of rangeland resources.
- The productivity of African rangelands is heterogeneous in space and variable over time, thus flexibility is necessary in livestock management approaches.

Effective tracking can be achieved in a number of ways involving the efficient use of a highly spatially and temporally variable fodder supply. One method is to de-stock through sales of livestock during drought and restocking once vegetation production improves. One objective of this study is to examine the effects of implementing this type of opportunistic management approach, the primary goal of which is to reduce livestock mortality as a result of unanticipated drought conditions. The impact of mortality on total herd efficiency is demonstrated by Du Toit et al. (1995). The results obtained from a simulation program modelling animal production show the marked detrimental effect of mortality on animal production, with certain breed types responding more favourably than others. This provides a motivation for managers and researchers to investigate strategies that allow for reduction of mortality rate in these production systems.

Campbell et al. (2000a) refer to the research that has been done in the past decade in semi-arid regions as giving rise to a "new rangeland science", proponents of which argue in favour of the adoption of tracking strategies as opposed to adhering to a constant, conservative stocking policy. Included among the concepts that this "rangeland science" supports are that:

(i) Rangeland systems operate under systems of multi-, dis- or non-equilibria;

(ii) The concept of carrying capacity is of minimal value;

(iii) Pastoralists should not adhere to a single conservative stocking rate, but rather adopt an opportunistic strategy where numbers will fluctuate widely in response to good and bad seasons;

(iv) Overgrazing or environmental degradation is minimal; and

(v) Opportunistic strategies give the highest economic returns compared with other strategies.

Campbell et al. (2000a) present results that compare the performance of four cattle management strategies, simulated with data collected from communal cattle farming areas in Zimbabwe. These are:

(i) "the opportunistic strategy", which represents a loose tracking scenario, characterised by consistently high stocking rates during good seasons and substantial stock mortality in dry seasons as little or no pre-emptive de-stocking is practised in the face of looming drought;

(ii) "the tight tracking scenario", which consists of a tracking and buffering approach, controlling stocking rate in order to maintain equilibrium between cattle numbers and forage availability;

(iii) "the conservative tracking scenario", which also implements a fluctuating stocking rate, but this is lower than that of the "tight tracking scenario";

(iv) "the conservative scenario", which maintains cattle numbers at a constant, conservative stocking rate.

The economic performance of these strategies were compared for two different regions where communal farming was being practised. One area was characteristically semi-arid, with low and highly variable mean annual rainfall. The other region experienced comparatively higher and less variable mean annual rainfall. Their results suggest that strategies implementing conservative stocking rates perform better economically than those implementing opportunistic stocking rates. They also point out that tight tracking scenarios, that de-stock and restock in an attempt to "keep up" with fluctuations in available forage, are likely to be accompanied by severe economic losses. In this study reported by Campbell et al. (2000a), the conservative policy is found to produce the highest economic returns of the four policies investigated. It is only when price variability is excluded from the calculation of economic returns that one of the other strategies is able to emulate the performance of the conservative approach. In this case, the conservative tracking strategy achieves similar economic return to those of the conservative strategy. In addition, the tight tracking policy is likely to result in rangeland degradation, since re-stocking takes place immediately in the post-drought period, without any interval in which vegetation can recover pre-drought production levels. This is in contrast to opportunistic and conservative strategies, which tend to avoid negative impact on vegetation with high stock mortality in drought seasons.

2.6. AN ANALYTICAL FORMULATION OF PRE-EMPTIVE OFFTAKE

This section describes how a simple analytical approach can be employed to investigate the implications for a manager who chooses degrees of stock offtake by attempting to predict forthcoming climatic conditions. Scenarios of a correct prediction of drought with that of an incorrect prediction are compared, using an exponential equation to represent population growth.

Let the population p at time t be described by the equation:

$$p(t) = p_0 \, e^{rt} \tag{1}$$

where

p_0 = the initial population at t =0,

r = the specific growth rate of the species.

In one year, the growth of the population is:

$$\Delta p = p_0 e^{rt} (e^{r} - 1) \tag{2}$$

Implementing a management strategy that maintains a constant annual stocking rate of p_0 , the annual offtake O_a is then :

$$O_a = p_0 \ (e^{r} - 1) \tag{3}$$

Consider the scenario in which the manager makes a certain prediction concerning the occurrence of a drought year. According to this prediction, certain reactionary policies are implemented, in which a percentage h, $0<h<1$, of the current population p_0 is removed for sale. The gain G made from this offtake is:

$$G = p_0 - p_H \tag{4}$$

where

p_H = the population following offtake,

and

$$p_H = h\, p_0 \tag{5}$$

In the case that the manager is correct in the prediction of drought conditions, the benefit will be this gain G. On the other hand, in the case where the prediction and corresponding offtake reflects an incorrect expectation of drought conditions, the net loss L is calculated as:

$$L = T\, p_0\, (e^r - 1) - (p_0 - p_H) \tag{6}$$

where

T = the time taken for the population to regain its pre-offtake level.

Assuming that the probability of a correct prediction of drought is α, the net gain G_{net} over a time period T is:

$$\begin{aligned} G_{net} &= \alpha\, (p_0 - p_H) - (1-\alpha)\, [T\, p_0\, (e^r - 1) - (p_0 - p_H)] \\ &= (p_0 - p_H) - T\, p_0\, (1-\alpha)\, (e^r - 1) \\ &= [(1-h) - T(1-\alpha)(e^r - 1)]\, p_0 \end{aligned} \tag{7}$$

and

$$T = \frac{1}{r}\ln\frac{p_0}{p_H} = \frac{1}{r}\ln\frac{1}{h} \tag{8}$$

If the management decisions are to reflect more correct predictions than incorrect predictions, this requires that the net gain G_{net} is positive, i.e. we require:

$$\frac{1-h}{(1-\alpha)\ln\frac{1}{h}} - \frac{e^r - 1}{r} > 0 \qquad (9)$$

In order for the manager to make a positive gain i.e. "win more than lose", the forecasting accuracy that is required for a desired level of offtake, and for various specific growth rates can be calculated from this simple model. This is represented graphically in Figure 4 below, where o = 1– h represents the amount of offtake and r = 0.10.

It is clear that as the desired proportions of offtake increases, so must the manager's forecasting accuracy improve in order for continued economic benefit to be derived from pre-emptive offtake.

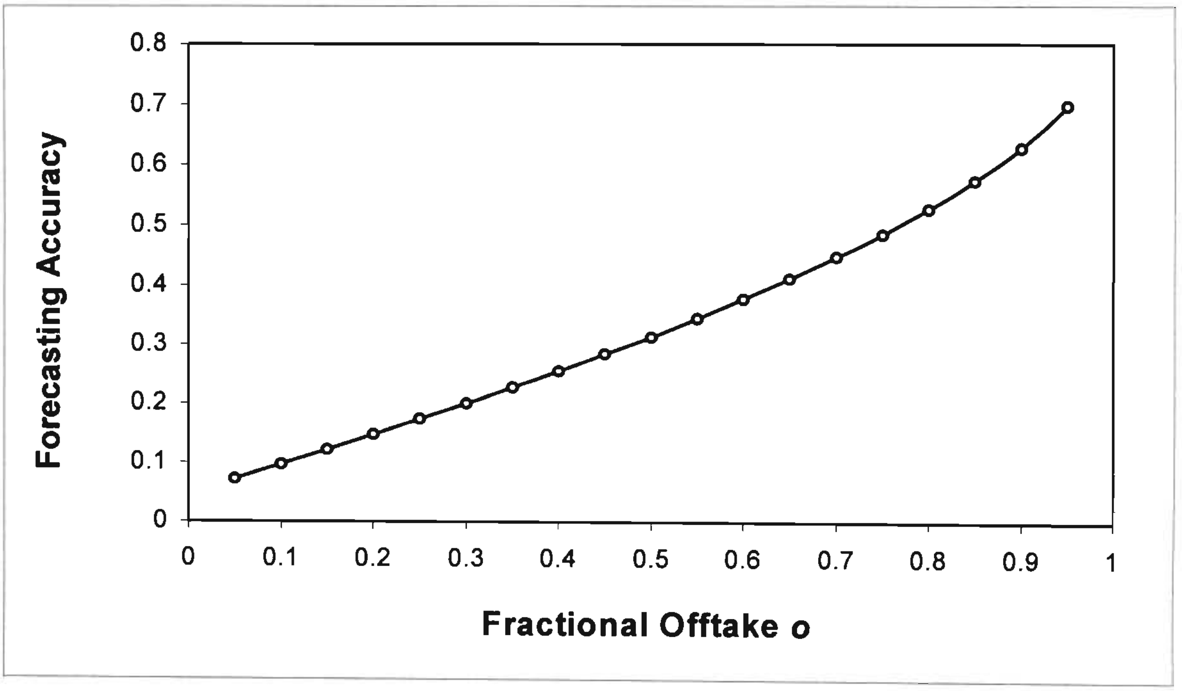

Figure 4: The relationship between forecasting accuracy and proportion of offtake.

This model appears to indicate that, given a "fair coin" accuracy of prediction, the benefit from pre-emptive offtake will exceed that of imposing a constant stocking approach. However, this result must be qualified by considering the situation in the long-term. Even in highly variable climates, severe drought prompting drastic de-stocking is not an annual event. In fact, we can safely assume that this does not occur more than two or three times in a 20-year period. Assuming a 50% probability of a correct prediction of drought, this implies that the manager makes the correct decision to de-stock only once (possibly twice) over this time span, and makes incorrect decisions, from which potential productivity is lost as the population takes time to regain prior levels. Viewing the net gain over a time span of 20 years, then, has the result that the net gain of the pre-emptive manager is rendered negligible in comparison to that of the manager implementing constant stocking levels. This analysis is useful in understanding certain results arising from the investigations that follow.

In Chapters Three and Four, we describe a model developed for the simulation of the dynamics of a semi-arid grazing system, with cattle as the grazing herbivores. This model is used to examine the impact of, and comparison between, constant and tracking management strategies on income from stock sales, variability of this income and drought-induced mortality. In addition, we examine the effects of assessing projected future income on current decision-making.

CHAPTER THREE

SIMULATION OF A SEMI-ARID GRAZING SYSTEM

3.1. INTRODUCTION

The term "semi-arid grazing system" is used to describe grassland systems that are typically characterised by a short rainfall season, with rainfall that is highly variable and for which extended dry periods are common. In the light of the preceding discussion, it is useful to apply a simulation model to investigate the influence of various environmental scenarios in these systems, particularly as climatic variability has such a profound impact on the profitability of livestock enterprises. Drought-induced mortality negatively affects production and hence output, and stocking rates are typically lower than in less variable climates due to the lagged recovery time of the herd following drought conditions (Illius et al., 1998). In modelling the dynamics of rangeland systems, it is important to bear in mind that these dynamics are strongly influenced by a management regime, which in turn is dependent on the objectives of livestock producers and the constraints they face. For example, whether a farmer is risk-averse or risk-neutral will influence his stocking policies and hence his responses to climatic conditions and market influences.

Mathematical models for both deterministic and stochastic environments have been implemented with varying degrees of accuracy and success. In reality, there are no natural systems that are truly invariant, with the result that true deterministic systems are mathematical abstractions. However, although they fail to capture the total influence of slight fluctuations in the system under consideration, they prove to be mathematically "friendly" and useful for studying the system's qualitative dynamics. When large, as opposed to slight, fluctuations characterise a particular system, it is necessary to undertake a stochastic modelling approach that captures the effect of these variations on the system dynamics. Semi-arid grazing systems are considered to be highly variable environments, with spatial and temporal variability being factors of primary influence. This high inter-annual variability, in conjunction with the fact that management options are implemented in cycles (Stafford Smith, 1996), invites the design and implementation of dynamic models to simulate these systems.

It is a widely-held opinion in recent times that the vegetation dynamics of rangeland systems are influenced in the main by rainfall as opposed to grazing. (Ellis and Swift, 1988). However, Noy-Meir (1975) developed models that suggested that a discontinuous vegetation collapse indicating range degradation could occur should a threshold stocking rate be exceeded. Such changes in vegetation density and distribution represent discontinuous and often irreversible switches between the multiple equilibria of the system. For example, the system can switch from a stable and resilient production state that is constituted of palatable species and has a high production efficiency, to one where unpalatable species invade the system; the latter state is still stable and resilient, but it now supports only a low level of productivity (Stafford Smith, 1996). Ideally, then, models of such systems should take into account the existence of multiple locally-stable states, and the influence of both grazing pressure, extreme climatic conditions, such as drought, and the management regime on the transitions between states. It is argued that the transition between states is a function of exogenous events; however the probability of transition for a particular perturbation varies with the management regime (Perrings and Walker, 1997; Perrings and Stern, 2000). Hence the management options practised by farmers have a marked effect on rangeland dynamics.

3.2. MODEL FORMULATION

A stochastic, dynamic model, termed SimSAGS (**Sim**ulation of a **S**emi-**A**rid **G**razing **S**ystem), has been developed by Illius, Gordon and Derry (1998, 1999a, 1999b) for simulation of a semi-arid grazing system. This model is adapted for Namibian vegetation conditions and rainfall, and an economic component incorporating a market price structure is added. The model is temporal and is designed to capture the effects of climatic variation on plant production and herbivore dynamics. The model structure constitutes a frame-based approach which allows each combination of interacting components to define a state for the model; transitions between states occur upon alterations in the interactions (Derry, 1998).

It is constituted of three sub-models: a plant growth model that has daily rainfall as input for vegetation production, an animal dynamics model and an economics component that calculates revenue from sales. The vegetation production component allows for estimation of daily plant growth; once this is calculated, the model simulates herbivore diet selection, intake and metabolism, as well as defoliation of standing plant biomass by grazing. Animal growth, reproduction and mortality are simulated as a function of intake net of expenditure. The coupling of animal dynamics and plant production allows the underlying mechanisms to dictate the performance of the system over the chosen time scale. The model makes provision for management options to be specified in terms of desired stocking level, amount and timing of offtake in response to rainfall conditions and selection of required offtake from specified age and sex classes. Specifically, alternative stocking approaches (constant versus tracking strategies) can be compared in terms of income, variability of income and mortality.

In the absence of management control of stocking levels, animal numbers are controlled by forage availability and natural biological rates of birth and mortality, the former being a function of rainfall inputs to the system. Simulation of the system in this way allows for the long-term ecological carrying capacity to be predicted. Rainfall data from seven rainfall sites across Namibia, supplied by the Namibian Meteorological Services, was used to generate a transect graph of mean annual rainfall versus ecological carrying capacity.

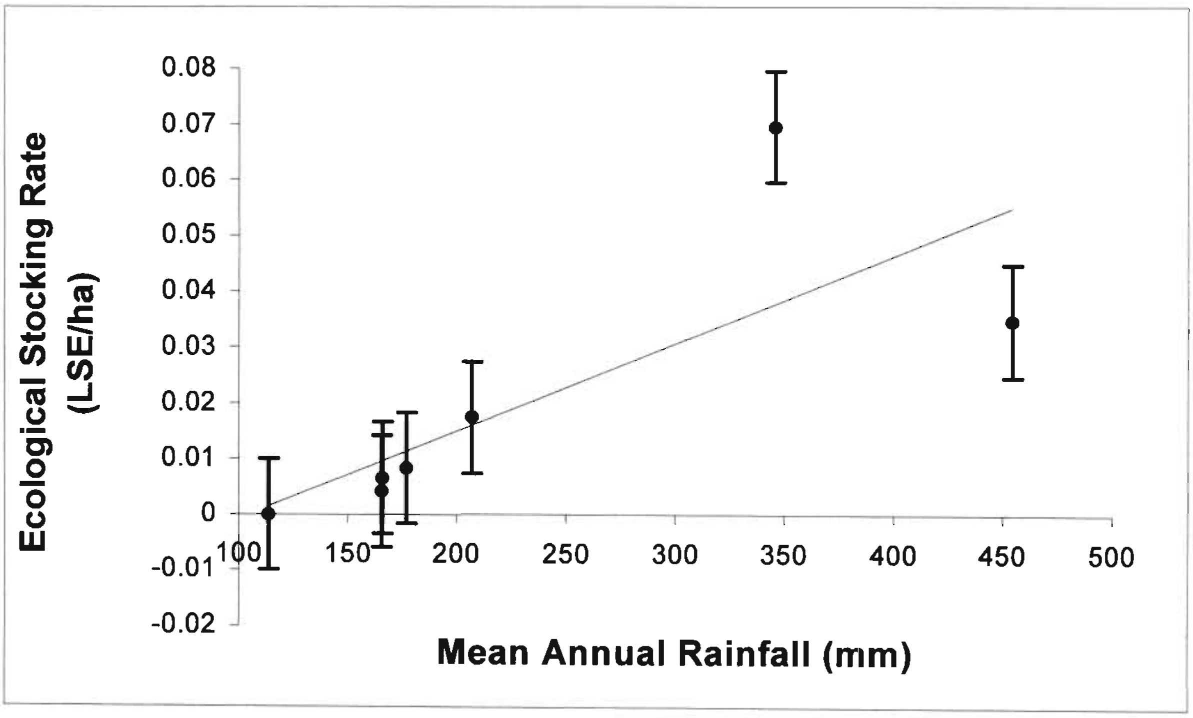

Figure 5: Transect of Ecological Stocking Rate vs Mean Annual Rainfall.

This relationship is then employed in deriving the equation used to implement adaptive stocking strategies, in which the target stocking rate is adjusted as a function of the current season's rainfall, with the slope of the transect adjusted according to the given year's cumulative rainfall to mid-March. So the equation used in calculating the adaptive stocking rate regression is:

$$ASR = \frac{R_1}{R_2} mx + c \qquad (10)$$

where

R_1 = long-term mean annual rainfall for the given site,

R_2 = long-term average rainfall cumulative to 15 March for the given site,

and,

m, c = parameters for the slope and intercept respectively, obtained from the regression equation for the Namibian transect.

The transect relationship has an R^2 value of 61%. It is recognised that this does not necessarily account satisfactorily for the variability in the data set, and note that this could prove to be a weakness in the application of the adaptive stocking management strategies.

3.2.1. Temporal Scale and Rainfall

The simulation interval is a year starting in September, this being the start of the rainfall season. The model runs on a daily iteration interval, with the use of daily rainfall data to drive primary production. The daily time step is facilitated by the availability of long-term historical daily rainfall records available for a distribution of sites across Namibia. The temporal nature of the model captures the changes in vegetation growth over time in response to rainfall and grazing impacts. In addition, changes in animal condition in response to forage availability and grazing intake can be tracked.

Stafford Smith et al. (1996) find that the sequence of rainfall years has a significant impact on the optimal stocking rate predicted using their simulation model, RISKHerd. Preliminary work (Illius et al., 1998) indicates the sensitivity of simulation results to rainfall sequence. Hence, rainfall sequences are generated stochastically from historical 26-year sequences and 20 replicates performed for each simulation. The sequence of annual rainfall for each replicate is randomly generated from the historical data, with each rain year numbered from 1 to 26. For example, the first replicate might have the years in the following order: 10, 17, 1, 26, 5, etc. while the second replicate might have a sequence 25, 2, 7, 11 etc. Thus, each replicate has the same mean value and co-efficient of variation as the historical data set but the sequence effect is controlled by randomising the order of rainfall years. Once a set of sequences and replicates had been generated stochastically, all management strategies were exposed to the same set of 20 sequences to exclude the influence that rainfall sequence has on the long-term dynamics of the system. In order to minimise as far as possible the effects of the initial parameter values chosen, each 26-year sequence is preceded by a simulation run of 5 years using long-term average daily rainfall figures which allows the system to stabilise to a steady state.

In choosing the number of replicates to be performed for simulations runs, it is necessary to weigh the desired level of accuracy against computational effort and time, since the time taken to run a simulation increases greatly as an increasing number of replicates are performed. Thus, an analysis of the model output against the number of replicates is useful. In undertaking this analysis, the model was run in the absence of management offtake responses in order to compare the resultant ecological carrying capacity (ECC) for an increasing numbers of replicates. Then a moving average of the mean ECC over a given number of replicates was calculated. Each of these values was compared with the long-term

ECC over thirty replicates. Figure 6 demonstrates that values converge to within 5% of the long-term value within 20 replicates. Thus, it was decided that 20 replicates would adequately capture the relevant model outputs. Then the output values are averaged over the 26 years of a simulation run to provide a mean annual value; these mean annual values are averaged over the 20 replicates.

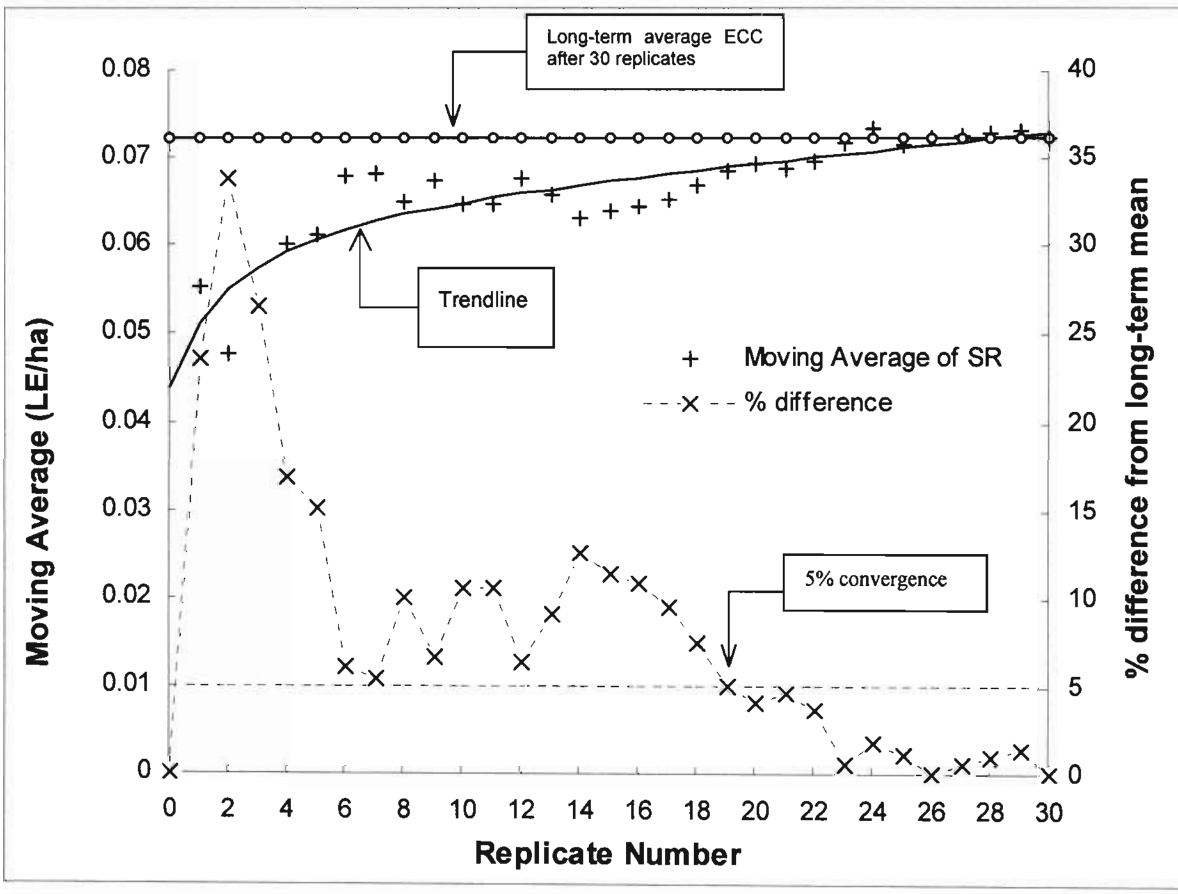

Figure 6: The convergence of ECC to long-term value with an increasing number of replicates. It is apparent from this graph that 20 replicates are sufficient to ensure convergence to within 5% of the long-term ECC.

3.2.2. Plant dynamics

A detailed vegetation model forms a sub-component of the overall model (VELD, Dye, 1983). It comprises a water-budget sub-model linked to a plant-growth and allocation to plant parts sub-model. The model is detailed extensively in Dye's (1983) doctoral thesis and we provide a summarised outline of the model and its sub-components below.

VELD was developed to simulate grass growth in a semi-arid savanna region dominated by *Heteropogen contortus* in South-Eastern Zimbabwe, where annual rainfall is approximately 600 mm. The model is temporal, in order to simulate the variation of vegetation distribution and plant growth with time, influenced by rainfall and grazing pressures. Daily rainfall, pan evaporation and humidity data serve as inputs for the calculation of primary production and allocation of growth to plant components on a daily basis. Existing standing biomass present and vegetation growth in response to rainfall is updated daily. Biomass is measured in units of $kg.ha^{-1}$ and is partitioned into plant components of live stem, dead stem, live leaf and dead leaf. VELD incorporates a water-balance component with the plant growth model. The latter describes grass growth, decay of plant matter and defoliation as a result of herbivory, and is applied to growth of perennial grasses and woody browse. State variables for grasses are carbohydrate stores, green (live) leaf and dead leaf, fallen seed, green (live) stem with seed, and dead stem. For the purposes of this study, initial tree biomass was set at a low value, representing a system that is primarily constituted of grass species. The water-balance component is formulated in terms of moisture stores at various soil depths. These stores are augmented by infiltration and runoff arising from daily rainfall, and depleted by evaporation into the atmosphere and transpiration by plants. Transpiration governs net plant growth, which is allocated to plant component parts. Since transpiration only occurs from green leaves, the rate at which green leaves die affects net plant growth; this rate increases with the age of the leaves i.e. as a function of time, and with declining available soil moisture.

The digestibility of the grass components is calculated, and used in calculating herbivore intake and hence energy balance relationships determining animal growth and body condition (see *Herbivore Dynamics* below). The proportion of live to dead material consumed is dictated by the proportion of live to dead material in the grass sward, as well as the degree of herbivore selectivity, which in turn depends on the animal's mass. The digestibility of plant components governs the digestibility of the herbivore's diet d, which can be calculated according to the following equation (Illius and Derry, *pers. comm.*):

$$d = PL_{diet} * d_L + (1 - PL_{diet}) * d_d \qquad (11)$$

where:

PL_{diet} = the proportion of live material in the diet,

d_L = the digestibility of live material, and

d_d = the digestibility of the dead material,

and

$$PL_{diet} = (PL_{sward})^n \qquad (12)$$

with

$$n = c * M^d \qquad (13)$$

where

PL_{sward} = the proportion of live material in the sward,

M = the actual mass of the individual (kg),

n = indicates the selectivity of the animal as an allometric function of mass (assumes values between 0 and 1), and

c, d = parameters relating selectivity to grass type.

3.2.3. Herbivore dynamics

In considering the long-term dynamics of plant-herbivore ecosystems, it is important to capture aspects of the population dynamics such as the population distribution over various age and sex classes. This is influenced by a number of factors; for example, Du Toit et al. (1995) observe that mortality rates in neonate (newborns and suckling calves) and weaner (weaned calves) age classes have a marked effect on animal productivity and hence on herd efficiency. In modelling population distribution, the modeller endeavours to incorporate the different energy requirements, mortality susceptibility and responses of different herd classes to food availability, into the simulation of the herd dynamics.

SIMSAGS simulates animal dynamics mechanistically, with equations describing births, mortality and animal intake governing the population dynamics and animal condition (Illius et al., 1998). Animal intake of forage includes the influence of diet selection, and is modelled as a process starting with the individual bite leading to a calculation of daily nutrient intake, metabolism, energy balance, reproduction and mortality. The degree of selectivity practised depends on the balance struck between the rate of consumption and the nutrient content of the diet. The model assumes that, on a daily basis, forage selected for grazing from that available will be that which offers the highest nutrient content and hence the greatest potential energy intake. This mechanistic modelling approach is facilitated by the progress that has been made in recent decades in quantifying the relationships between vertebrate herbivores and the vegetation on which they feed (Illius and Gordon, 1998). In addition, this approach allows for secondary production (in the form of livestock growth and reproduction) to be simulated as a function of rainfall.

The herbivore sub-component has provision for more than one species, although this study considers just one species, namely cattle. The species is specified in terms of the mature mass of each sex, and the herd is classified into age and sex classes, specifically neonates (suckling calves), juveniles (weaned calves less than one year old) and adults. To facilitate comparisons between animals in different age classes, the measure of metabolic liveweight is employed, and immature animals are specified in terms of the fraction of a Livestock Equivalent that they constitute. Rates of birth and mortality determine the animal state variables of numbers in each age and sex class.

Modelling populations in terms of the individuals constituting the population as opposed to a single herd unit captures variation in maturity, fat mass and reproductive potential between individual members of the herd, as well as accounting for interactions between individuals, an approach advocated by DeAngelis and Gross (1992). A disadvantage of this approach is that accounting for each individual in a typically large population results in high computational complexity and long simulation times. Scheffer et al. (1995) suggest an approach in which herd members are modelled as so-called "superindividuals", where each model individual is considered in terms of the number of real individuals it represents. This allows for a shift from a real individual-by-individual model to a cohort representation, without sacrificing knowledge of variation within the herd, that reduces computational time and allows similar individuals to be grouped together to form classes of individuals. Effectively, this approach sees the population represented in terms of histograms of various individual characteristics, such as fat mass and fat-free mass in our case. The modeller is able to control the number of individuals represented by a super-individual (the internal amount), and hence control how finely or coarsely the population is represented, as well as the degree of computational burden.

Since animal condition is a key factor in determining the market prices offered for sales of beef, it is necessary to have an indicator in the model that tracks changes in animal condition. Animal condition is dependent on net energy intake, which is associated with factors such as the animal's size, physiological needs, forage abundance, and feed attributes such as energy concentration, digestibility, protein content, fibre content and cell-wall content (Kahn and Spedding, 1984). Quantifying intake by the calculation of the individual fat reserves accumulated or lost over time allows the physical condition of each individual member of the herd to be quantified. This so-called "fatmass" is then indicative of reproductive capacity, survival probability and sub-cutaneous fat content. The latter constitutes one of the factors influencing the classification of beef into the various price categories. Stafford Smith (1996) concurs that mortality ought to be governed by body condition, or the rate of change of body condition. In addition, physiological status largely dictates rates of conception and reproduction, given the assumption that there are sufficient males present to interact with fertile females. Fatmass and current fat free-mass constitute two state variables in the model: fat-free mass (L) represents an individual's size and degree of maturity while fatmass (F) serves as an energy store and indicates the physiological maturity and energy balance history of an individual (Illius and Gordon, 1998). The maximum fatmass of a given individual is formulated as an allometric function of that individual's weight. Fat-free mass is constituted of protein, water and minerals: it is calculated as a function of the animal's capacity for net protein synthesis, and restricted by nutrient intake if this is insufficient for protein growth. The formulation of equations governing fatmass and fat-free mass, as well as the energy costs of reproduction, is described in detail in Illius and Gordon (1998).

Thus, the herbivore component of SimSAGS has biological rates of reproductive capacity and mortality related to animal condition, which is measured in terms of an individual's fatmass. Conception for an individual female is deemed to be possible as long as the female's fatmass exceeds a threshold value that is half her maximum possible fatmass; in this case conception probability is 1. Should a female's fatmass fall below this threshold value, conception probability is zero. Hence, the probability of conception is modelled as a logistic function of animal mass, since this probability is a function of the individual's body condition and maturity (Illius and Gordon, 1998). The assumption is made that each pregnant female will produce one calf, and birth ratio of males to female calves born is 0.5.

Probability of mortality is handled in a similar vein, with the animal deemed to have zero survival probability when its fatmass falls to zero, and experiencing an increasing chance of survival as its fatmass increases to its maximum possible percentage of total body mass. Conditional mortality as a consequence of starvation is explicitly modelled and is differentiated from "background" mortality i.e. mortality due to causes that are not explicitly modelled such as disease. The model calculates fat mass for each sex, age and reproductive class, along with the corresponding metabolic measure of fat-free mass, according to the individual's calculated energy balance and nitrogen intake, and birth season is governed by animal condition. Energy balance relationships are determined from daily intake from grazing less the energy expended on movement and resting metabolic consumption, and are updated on a daily basis accordingly. Since an individual's energy balance history governs its metabolic mass and hence its biological rates, and is in turn governed by its intake of vegetation, these relationships provide the link between herbivore dynamics and vegetation biomass dynamics. The assumption is made that individuals will select that forage which maximises their daily intake, and this primarily depends on time spent grazing, subject to certain constraining factors. One such factor is bite size, where bite size is measured as the mass of plant tissue that can be cropped at a single instant, and has units of grams per bite (g/bite) (Illius and Gordon, 1987). In fact, analysis of herbivore functional response by Spalinger and Hobbs (1992) shows bite size to be the variable that exerts the greatest influence on intake rate. Bite size is governed by the morphology of the animal's mouth, the volume of the plant and its bulk density in g.cm^{-3} (which is a function of height and biomass of the vegetation), as well as the animal's incisor arcade breadth* and bite depth (the depth of insertion of incisors into the sward. Another constraint on daily intake is digestive capacity, literally the size of the individual's stomach; cattle are non-selective bulk and roughage eaters, with a tendency to graze relatively low quality food comprising mainly grass.

For any given quality of forage, herbivore intake is limited by an upper threshold governed by the capacity of the individual's stomach and the rate at which digestion of the given food source can occur. In addition, animal intake and digestion is influenced by the animal's grazing of plant parts, comprising live and dead leaf, and live and dead stem. Stems have a lower nutrient content and a higher fibre content than leaves. Hence it is useful to include the relative proportions of various plant parts in a sward as a component of the vegetation dynamics. This allows animal performance to be more accurately simulated. The digestibility of the animal's diet is a primary factor governing intake – this digestibility is primarily determined by, and inversely related to, the fibre content and the degree of lignification (the proportion of live to dead matter present). In other words, digestibility of the sward is governed by the relative proportions of the plant parts comprising the sward and their maturity (Illius, 1985). In the later part of the season, the amount of dead material present increases, and this has a marked effect on the condition and intake of the herd. In addition, food intake increases with the digestibility of the food (Mentis, 1977). Fryxell (1991) evaluates forage quality in terms of digestible energy content, and holds that, in most cases, digestible energy simply varies with dry-matter digestibility. In addition, his model allows digestible energy content to restrict maximum daily intake over the entire range of quality values – this to incorporate the limitation effect of digestive

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* See Appendix 1

capabilities of ruminants on daily intake of energy. Energy expenditures (or costs) are partitioned into two categories: thermoneutral resting metabolic expenditure and foraging expenditure. Resting metabolic expenditure, or basal (fasting) metabolism, is the rate of energy consumption of an animal at rest; it is non-linearly related to live mass, and includes maintenance and activity requirements (See Appendix 1). The increment in energy consumption of an active animal over that of resting metabolic consumption is influenced by degree of activity, physiological and reproductive status and weather conditions. Data indicates that the energy consumption of a free-ranging individual does not, on average, exceed twice the basal metabolism (Mentis, 1977). Energy and protein costs for pregnancy and lactation in females are included in the calculation of the daily energy balance, while the decreased intake and increased patterns of movement observed empirically in rutting males during mating season are incorporated as losses in the energy balance relationship for the relevant individuals (Illius and Gordon, 1998).

In summary, then, animal intake is modelled in terms of a functional response that quantifies the relationship between daily intake and forage abundance. The digestive kinetics model of Illius and Gordon (1991, 1992) has daily dry matter intake of a herbivore as a function of diet selectivity, forage properties (abundance and standing biomass), digestive capacity and animal size, in the following equation:

$$I = I_d\,(1 - e^{-b\,(B-r)}) \qquad (14)$$

where

I = daily dry matter intake (kg),

I_d = an asymptote defined by the animal's digestive capacity,

B = vegetation biomass ($kg.ha^{-1}$),

r = lower limit of residual biomass below which animals cannot graze ($kg.ha^{-1}$),and

b = size-related constraint.

The parameter b accounts for the influence of body size, and hence bite size and metabolic requirements for an individual, on dry matter intake. As such, b is modelled by Illius and Gordon (1987) as an allometric function of mass with a negative exponent:

$$b = p^*M^{q} \qquad (15)$$

where

p, q = vegetation-type specific parameters.

I_d specifies the maximum daily intake in kilograms under digestive constraints, which are the digestibility of the diet and the individual's size; it is calculated according to the following equations depending on whether the material being grazed is grass or browse respectively (Illius and Gordon, 1998):

$$I_d = 0.09d^{1.1} A^{0.81} u_g \qquad (16)$$

or

$$I_d = 0.13d^{1.35} A^{0.77} u_g \qquad (17)$$

where

d = the digestibility of the diet (in vivo),

A = the mature mass of the animal (kg),

u_g = factor scaling gut capacity to body mass $= (M/A)^{0.75}$ (18)

M = the actual mass of the individual (kg).

Once daily dry matter intake is calculated, it is translated into daily energy intake EI (MJ.day^{-1}) by the following equation (ARC, 1980):

$$EI = 15.6 * I * d \quad (19)$$

E_{exp}, the net metabolisable energy expended is calculated from various components of energy expenditure. These equations are detailed in Appendix 1. Then, the daily change in fat reserves is the difference between energy intake and expenditure.

It proved necessary to make some adjustments to the model when implementing it with Namibian rainfall and vegetation biomass conditions, this as a result that simulated intake proved insufficient to sustain animals. Further investigation showed that the low and variable rainfall in Namibia leads to a high degree of clumpiness in vegetation (vegetation is sparsely distributed in clusters), which increases as basal cover and grass biomass decreases (Ward *pers. comm.*). This has the effect that although the biomass density is low, the density in a clump is high. In terms of the model's functional response, the low biomass density is interpreted as being very short, homogeneously-distributed grass, which the animals are unable to graze as it is not long enough i.e. the incorrect intake response was being simulated. Adjusting the functional response allowed for the adequate biomass density in irregularly distributed clumps of grass of grazable height to be recognised and included in the herbivore's intake. Another consequence of the vegetation clustering is that animals are forced to forage further as opposed to being able to graze continuously while moving. This means that greater energy is expended on movement, as well as limiting the amount of forage that animals can reach in a grazing day* – this resulted in a high starvation-

* Maximum length of time for which animals can forage in a 24-hour period; typically the number of daylight hours.

related mortality prior to adjusting the model for clumpiness, lower vegetation biomass and seasonal vegetation digestibility. In this study, maximum grazing time per day is set at 10 hours.

Figure 7 below demonstrates the natural dynamics (i.e. with no management interventions of offtake or restocking) simulated by the model using 26 years of historical rainfall data for the Windhoek site. The lagged response of the herbivore population to available forage (vegetation biomass present) is apparent. This lagged response is largely due to the population dynamics such as gestation (approximately 283 days (Gertenbach *pers.comm.*)) and mortality due to starvation (about one month with **no** available forage) occurring over a period of months rather than instantly.

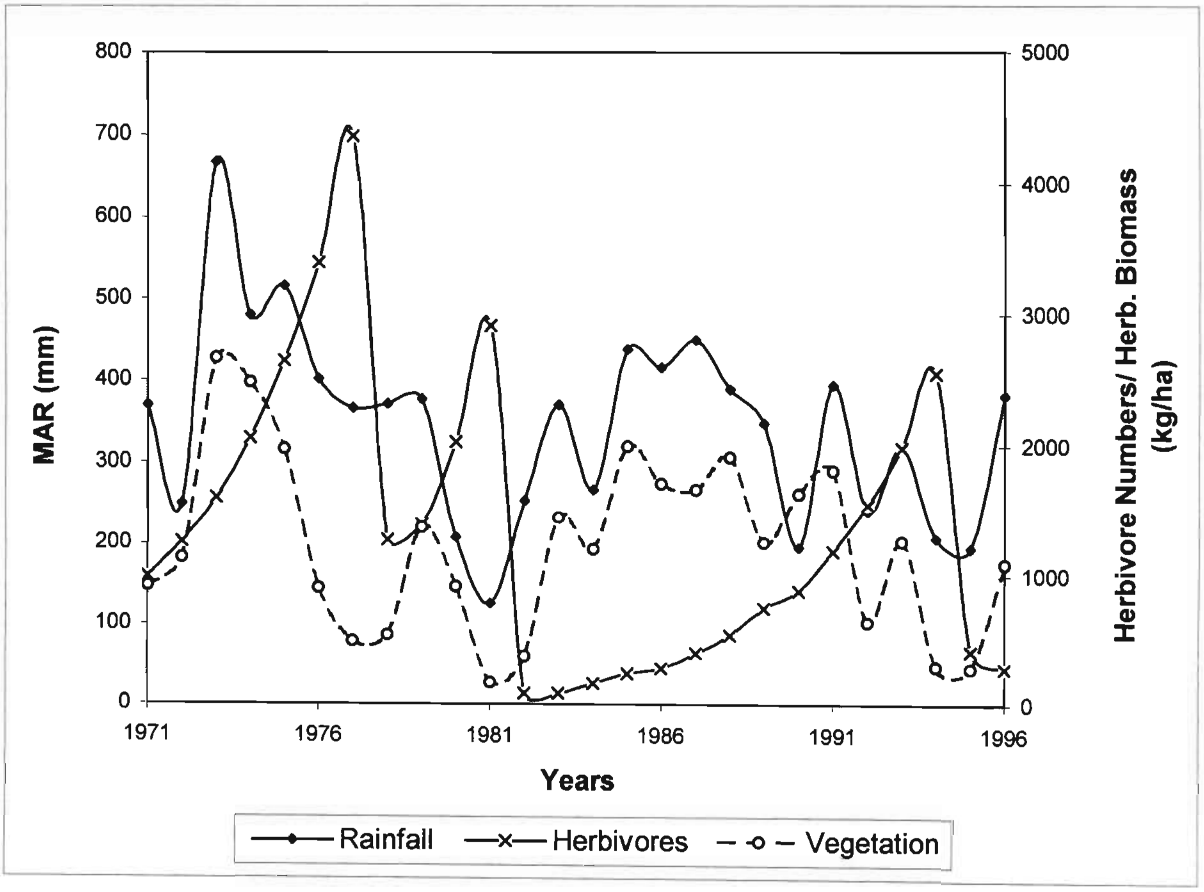

Figure 7: The effect of rainfall on herbaceous growth and herbivore numbers. The primary y-axis shows mean annual historical rainfall (mm), while the secondary y-axis reflects the number of cattle present and the herbaceous biomass (kg.ha^{-1}) present.

3.2.4. Economics

Carcass classification

Beef carcasses are graded primarily according to age class and sub-cutaneous fat content. Three age classes, A, B and C, form the major categories; these in turn are divided into seven sub-categories which describe sub-cutaneous fat characteristics of the meat. The model translates the fat mass demography applied in the "superindividual' histograms into this age class and fat content grading scheme. Then income is calculated as the product of offtake mass and the price specified as an input for a given category of meat.

Prices for beef fall into various categories governed by an international grading system. Carcass grading implies that different carcasses are graded in order of merit, from the most preferred to the least preferred grades. In the carcass classification system, the following carcass attributes are recorded:

- Carcass mass (kg)
- Age of the animal (A, B or C)
- Fat content of the carcass (0 to 6, with category 0 representing those animals with zero millimetres of sub-cutaneous fat and category 6 representing excessive fat content greater than 10mm)
- Carcass conformation (1 to 5)
- Damage to the carcass (1 to 3)
- Sex of the animal (only for bulls in categories B and C).

Age groups are defined according to the number of permanent incisor teeth present. This gives:

- Group A: 2 or less permanent teeth, approximately up to 2 years of age
- Group B: 1-6 permanent teeth, approximately 2-4 years of age

- Group C: 7 or more permanent teeth, over 4 years of age.

(*pers. comm.* Meat Board of Namibia).

Price data

Thirteen years of historical monthly price data supplied by the Namibian Meat Board were used in calculating revenue generated from simulated offtake. Prices are recorded for each of the three age categories, A, B and C, and each of the fat sub-categories so, for example, the price class for meat from an animal in the 2-3 year age class with maximum sub-cutaneous fat content would be designated B6. In order to provide price input for calculation of income from the model, it was necessary to obtain from the long-term historical price data an average monthly value for each price class. Before the average could be calculated, the upward trend in prices as a result of inflation had to be removed. This was achieved by applying a time-series analysis to the data.

A time-series approach applies a multiplicative model containing four components to account for variation in a data set, namely the trend, cyclical, seasonal and irregular components. The trend component describes the net influence of long-term factors that tend to operate gradually and in one particular direction over long time periods. This component is usually modelled by a smooth, continuous curve spanning the entire time series (Neter et al., 1988). The effect of inflation on price data constitutes such a trend component. Preliminary analysis of our price data indicated that this inflationary trend could be adequately described by applying a linear trendline (R^2 = 0.83), determined by a least-squares method. Once the trend equation was established, the trend was removed from the data set by finding the difference (residuals) between any given data point and the corresponding point on the trendline, and adjusting past data for these residuals upwards towards the average price in the final year of the data set. Then an average price for each month was calculated for input into the model.

Figure 9 below demonstrates the effect of removing the inflationary trend from the data set for price category A1, depicted in Figure 8 below, and calculating average monthly prices for this category. All other price categories were treated accordingly. Over all price classes, there is a pattern of price increase from the beginning of the rainfall season, tailing off into the dry winter months. This reflects the improvement in meat quality as the rainfall season impacts on forage availability and nutritional content, while the decline in animal condition during the dry season is reflected in the depressed prices over this period. It is this seasonality in prices that, among other factors, will influence the effectiveness of management strategies, measured in terms of income generated, variability of that income and stock mortality, since timing of offtake varies for the range of policies tested in this study and profitability is expected to be affected by this timing of offtake.

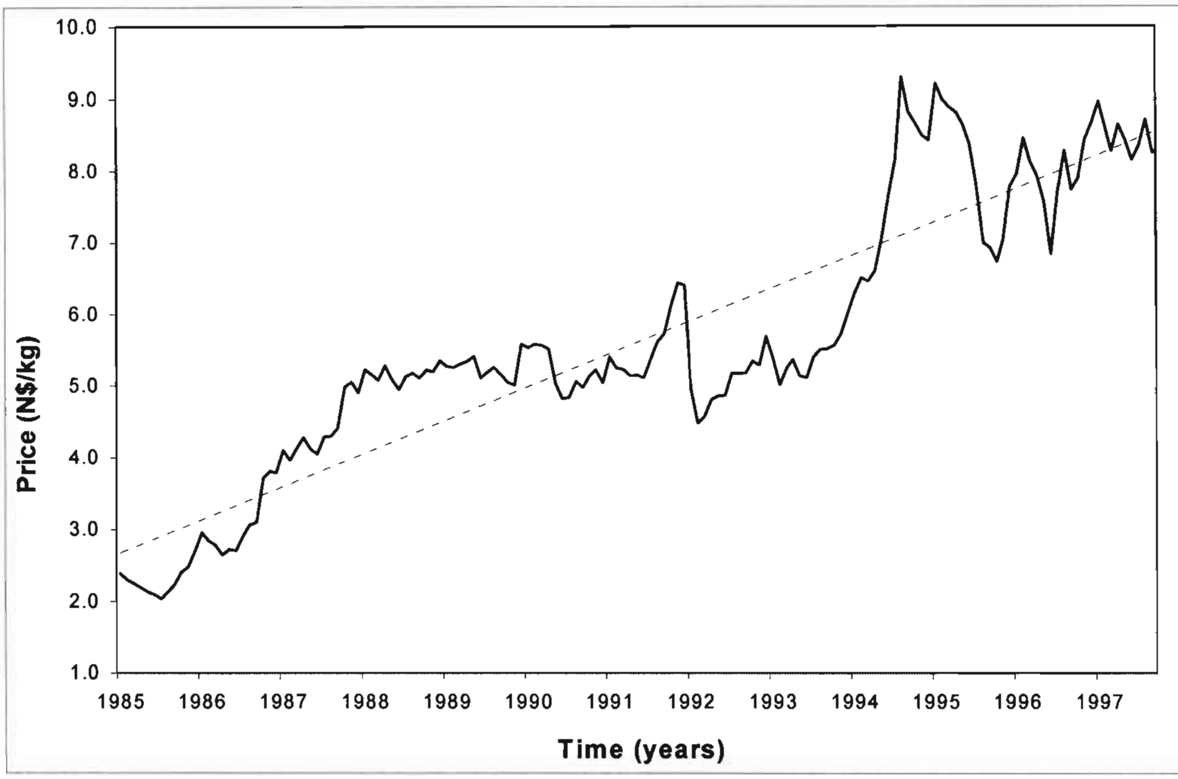

Figure 8: Inflation effects for price class A1 over time.

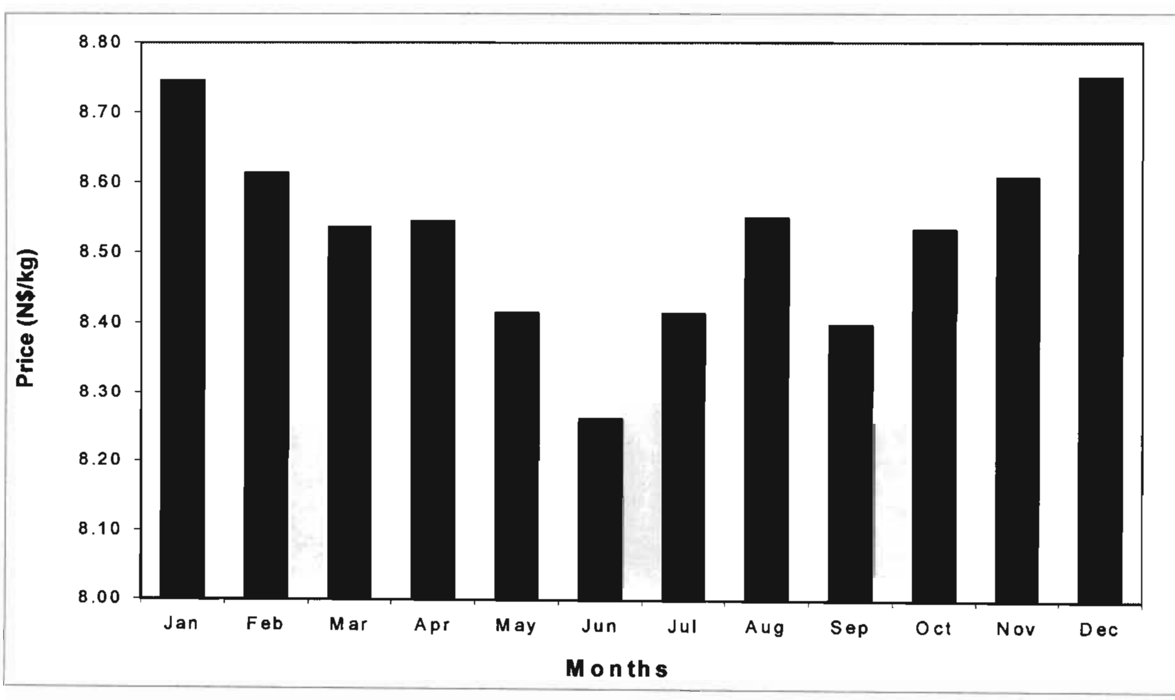

Figure 9: Average monthly prices class A1.

3.2.5. Management Options

Herd management is event-driven, with a given strategy being invoked on meeting a certain criteria at a specified time in the simulation. The model does not enforce a target herd structure, but does allow for the sequence of offtake from age and sex classes to be specified. Hence, given that a certain number of animals must be removed in order to achieve a target stocking rate, the manager is able to remove oldest females first, for example, followed by oldest males, and then move onto the younger groups should further removal be necessary. This appears to be practical, as in reality, farmers may, in certain cases, seek to maintain the breeding herd and remove animals whose fertility is reduced, while in other cases, farmers may desire to sell the younger and fatter animals first. In order to meet a given management offtake requirement, "individuals" are removed from the bars of the fat content histogram representing each age class (the superindividual approach suggested by Scheffer et al., 1995). The model allows for any age class to be reduced to zero if necessary with the exception of a restriction on the ratio of breeding females to males available for mating. The motivation for this restriction is that cow reproductive performance is considered to be a factor of primary importance in beef herd production. Thus management strategies are often aimed at providing cows with the best possible environment for reproduction (Cartwright et al., 1982). The number of cows allocated per bull depends on a number of considerations, including:

- Age of the bull
- Bull fertility
- Size of paddocks
- Vegetation
- Climate
- Topography

With Namibian topography and climate varying from North to South, Gertenbach (*pers. comm.*) recommends a ratio of 3-4 bulls per 100 cows for Southern areas and 5:100 in the Northern regions. This also accounts for the typical extensive grazing areas in which animals are likely to be scattered over a wide area, requiring a greater number of bulls to reach all the breeding cows. So, provision is made in the management options of the model for specification of the minimum number of bulls to breeding cows. This required minimum is examined during the offtake sequence; if it is not satisfied, restocking of the necessary number of bulls to achieve the specified ratio will only occur once females in the herd have attained satisfactory fat mass status for breeding.

Various management policies were simulated for the purposes of comparing the consequences of decision-making for outcomes of revenue generated from sales, variability of this revenue and stock mortality. Data from two different rainfall sites was used, namely Windhoek (MAR 346mm, CV 34.4%) and Hohenheim (MAR 220mm, CV 48%), with two categories of strategies, a constant stocking approach and an adaptive stocking ("tracking") approach, considered. A number of policies were implemented as sub-categories of these. The model makes provision, as a management option, for sales of females to be allowed or disallowed, as well as allowing or disallowing re-stocking in the event that mortality diminishes the herd to below a certain threshold value of the target stocking rate. Detailed descriptions of each strategy follow in Chapter Four. All strategies performed had female sales and re-stocking permitted.

3.2.6. Dynamic Management

Aspects of risk and expected return in agricultural production systems are often addressed by the implementation of models that employ dynamic decision processes involving timing of sales and varieties of marketing strategies (e.g. Garoian et al., 1990; Patrick et al., 1985; Rodriguez and Taylor, 1988). These activities are adaptive and dependent on the history of previous decisions and continuous revision of price and production expectations. Hence, the decisions made at each stage of production influence the decisions at each subsequent stage (Schroeder and Featherstone, 1990). The risk preference of a particular manager can be taken into account by applying the concept of a utility function, which is a measure of overall satisfaction and incorporates factors over and above pure profit such as risk preference. So a utility function is a formulation of weighted terms including risk and return expressions. Since levels of risk fluctuate, economists refer to "expected utility". The approach, then, is to optimise expected utility as opposed to optimising expected return, since the latter accounts only for the potential financial gains without including any other factors.

By incorporating a dynamic marketing approach into SimSAGS, alternative marketing strategies can be examined as part of an overall risk management approach. We examine the effect of delaying offtake for a specified period of time, with its associated level of risk. Our objective then is to calculate the expected income that arises from this delay by considering projected gains in fat mass typical for the month(s) under consideration. This expected income can then be compared with the financial return that would ensue should the manager chose to sell the same stock immediately. Further detail concerning the mechanisms governing these dynamic management simulations is given in Chapter Four.

CHAPTER FOUR

MODEL IMPLEMENTATION AND RESULTS

4.1. CONSTANT VS TRACKING STRATEGIES: HOW DO THEY FARE?

4.1.1. Descriptions of management policies

Descriptions of the range of management strategies that were tested in comparing a constant stocking rate with an adaptive ("tracking") approach follow:

- Constant Stocking Strategy ("control strategy") - "CSR"

  A constant stocking rate that optimises revenue is imposed as the manager's target value. According to this policy, two options allow the manager to either reduce his stock in the event of a surplus to the target stocking level by annual sales, or to augment stock levels by purchasing stock once annually. Stock sales are specified to take place on the 15 March of any given year, this being the end of the summer rainfall season. Stock purchase occurs at the beginning of December.

  The target stocking level that optimises revenue was determined by running a set of simulations across a range of stocking rates to obtain a relation between target stocking rate and revenue. This yielded an optimal target stocking rate of 0.08 LSE*.ha^{-1} for rainfall data from the Windhoek site, and 0.04 LSE.ha^{-1} for the Hohenheim site. The target stocking level set as a parameter differs from the average long-term stocking level ultimately achieved (in the case of Windhoek, this is 0.094 LSE.ha^{-1}) as births, mortalities and offtake cause this stocking level to fluctuate about the target level.

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* "Livestock Equivalent " is abbreviated LSE

- Pre-emptive sales in December – "PSD"

A pre-emptive sales strategy is implemented in conjunction with the control policy of maintaining a constant target stocking rate. This strategy seeks to mirror current management responses of Namibian livestock farmers, who implement a general "rule of thumb" by removing approximately one third of the herd when they anticipate that a drought season might be looming due to less than average rainfall at the beginning of the rainfall season. The timing of this removal varies but is normally implemented between December and March (Ward *pers. comm.*). During the simulation run, the occurrence of pre-emptive or "panic sales" is triggered on the specified date of 1st of December according to whether the cumulative rainfall up to this date surpasses a given threshold value. The threshold is determined as a specified percentage (set in our simulation runs at 70%) of the cumulative total of long-term average monthly rainfall from the beginning of the simulation year (1 September) to 1 December. Should pre-emptive sales be triggered by rainfall in the given year not reaching this threshold, a specified percentage of the total herd is removed and sold. As before, stock surplus to the target stocking rate is removed on 15 March with restocking (if necessary) in December.

- Pre-emptive Sales in February – "PSF"

This strategy is implemented as with the "PSD" option above, the only difference being that cumulative rainfall in the given year is evaluated at the end of February and compared with the designated threshold value based on long-term monthly average cumulative rainfall to this date. This serves to compare the influence that the timing of offtake has on net income. In addition, the comparison of these two approaches captures risk preference in management options, since a risk-averse manager will remove stock at the first indication of possible drought conditions, while a manager that is more risk-inclined will gamble by delaying offtake until the possibility of a drought is more apparent.

- Adaptive Stocking Rate, Capped – "ASR"

  A tracking strategy adjusts stocking rate in keeping with fluctuating herbage levels (which are governed by rainfall). The management objective is to maximise production in favourable rainfall seasons while minimising losses due to drought-related mortality. The annual target stocking rate is adjusted as a function of the current year's cumulative rainfall to mid-March, and monthly sales/restocking are effected according to this adjusted target. The adaptive stocking target is so formulated that a bumper rainfall season could see very high target stocking rates being realised. This necessitates the restraint of an additional control in the form of an upper limit on the stocking level ("cap"), to avert a population crash in subsequent years.

- Mortality Tracking – "MT1"

  An additional method of tracking is employed together with the adaptive, capped stocking approach described above. This seeks to capture the occurrence of drought-related mortality, and emulate a manager's response to it, by removing a specified number of stock (in this case, one animal) for each animal lost through starvation. The rationale behind this policy is to try and pre-empt further mortality by removing animals and thereby reducing the stocking rate and increasing available resources for the remaining livestock.

- Mortality Tracking – "MT2"

  This strategy is implemented as above for "MT1" except now, two animals are removed for each starvation-related death.

- Killing Out – "KO"

  The so-called "killing out" or dressing percentage is a measure of the mass of the carcass relative to the mature liveweight of the animal as a percentage (Gertenbach, *pers. comm.*). This policy seeks to simulate the practical consideration that abattoirs do not accept carcasses that are below a certain minimum weight. Thus, we impose a lower bound restriction on the mass of animals removed for sale/slaughter, with this lower bound being a specified percentage of liveweight, in this case 55%. The capped adaptive stocking rate is implemented as before with this additional restriction.

4.1.2. Performance evaluation of management strategies

The seven management strategies described above were simulated using historical rainfall data for two rainfall sites, namely Windhoek and Hohenheim, the former characterised by a higher mean annual rainfall and a lower variability of mean annual rainfall than the latter. Comparisons of performance of each strategy were effected using three measures: mean net annual income, variability of this income, and drought-induced mortality. The results are depicted graphically below, followed by a statistical comparison of results in Table 2.

Evaluation in terms of economic performance

The constant stocking and pre-emptive sales strategies were simulated with the target stocking rate set at the optimum value, as determined in the preliminary analysis and described in 4.1.1. The adaptive stocking rate for the four tracking strategies was calculated from the rainfall regression relationship as described in 4.1.1. The results are depicted graphically in Figure 10, which shows that the control policy of applying a constant stocking rate and the two pre-emptive sales policies outperform the four variations of adaptive stocking rate policies, with the latter delivering on average a 40% reduction in net annual income. There is little difference within the two categories, however. There appears to be little benefit to be derived from attempting to forestall stock losses from an expected drought as opposed to maintaining constant stocking levels. Similarly, no improvement in income is seen for a manager applying an adaptive policy by removing animals in proportion to mortality. This result seems counter-intuitive, as it was expected that the application of an adaptive stocking rate approach would improve economic returns. The results obtained encouraged a re-evaluation of the manner in which the management strategies were implementing offtake rules and impacting on herd dynamics: this is discussed in 4.1.3.

Evaluation in terms of variability of net annual income

Variability of income is considered to be a measure of risk. Thus, we evaluate the various management strategies described in 4.1.1 in terms of the co-efficient of variation of mean net annual income, and depict the outcome in Figure 11. Variability in income is markedly affected by climatic variation, with the region of lower rainfall and higher variability in rainfall producing substantially higher variation in income in comparison to the higher rainfall region. The comparison between the constant and pre-emptive strategies and the tracking strategies yields a somewhat surprising result. Economic theory traditionally links policies of higher return with higher risk. In this case, the opposite is seen to occur, with the strategies that offer the best financial returns also offering lower variability in income. This can be explained by the manner in which tracking strategies are implemented, since offtake (and hence income) is linked to rainfall and forage availability. Thus, the high climatic variability in these regions is responsible for this outcome, with amount of offtake varying widely from year to year. The constant and pre-emptive strategies provide a more stable source of offtake annually, and hence a lower income variability.

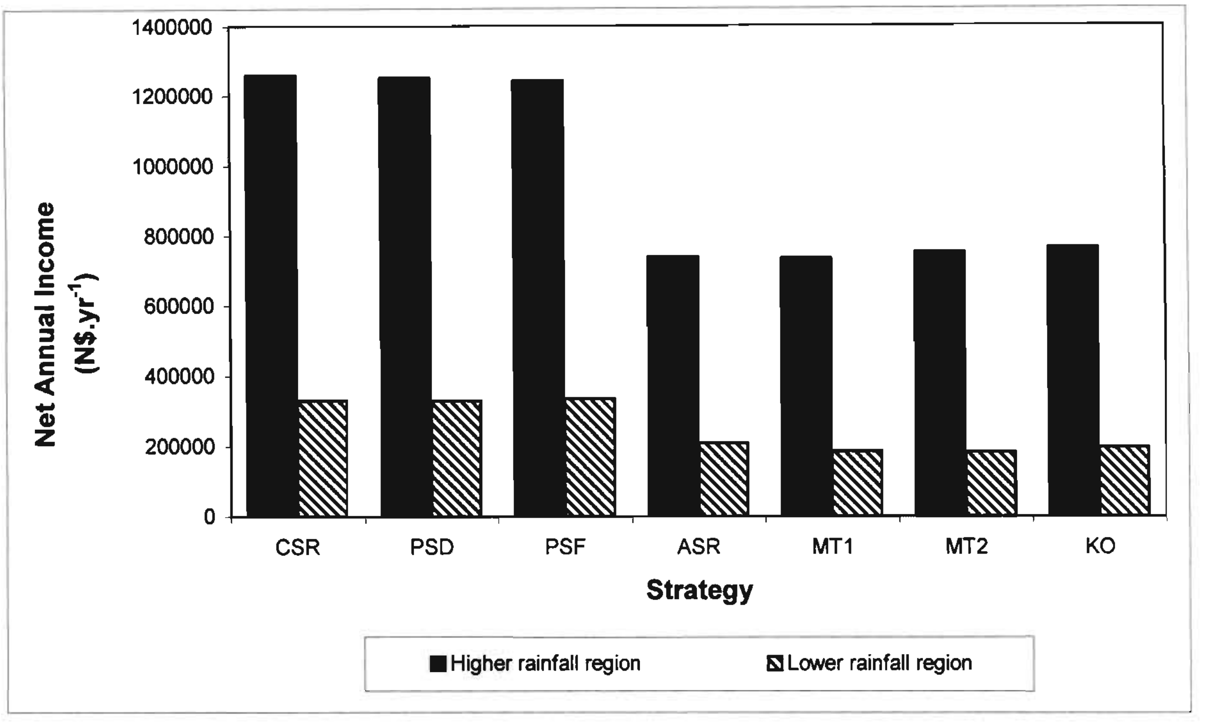

Figure 10: The performance of management strategies in terms of mean net annual income (N$.yr^{-1}).

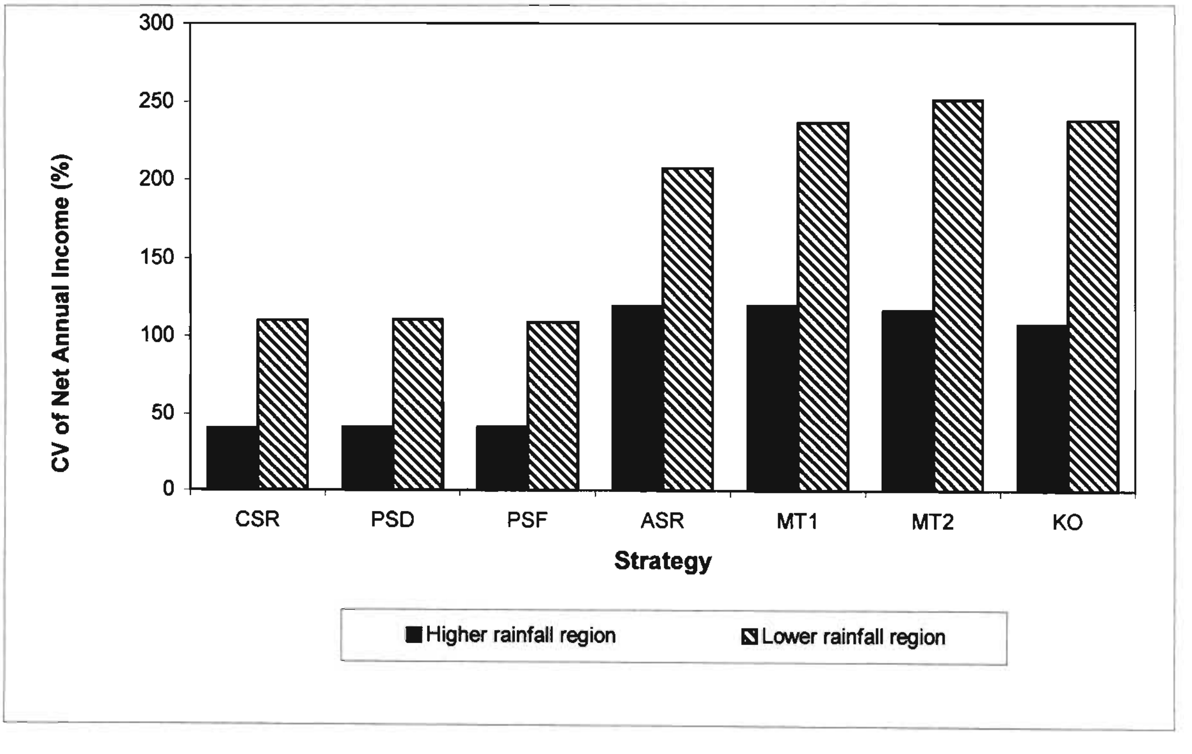

Figure 11: The performance of management strategies in terms of co-efficient of variation of mean net annual income (N$.yr^{-1}).

Evaluation in terms of mean annual mortality

Stock mortality is a measure of the loss of potential income. A risk-averse manager might set as his primary objective the limitation of stock losses. Thus, it is instructive to examine the impact that the various management approaches have on annual animal mortality. More specifically, the mortality in question consists of those deaths that are induced by diminishing forage availability i.e. starvation-related mortality. The results are shown graphically in Figure 12 and Figure 13. The former shows the mean annual mortality measured in number of heads, while the latter shows mean annual mortality as a proportion of the total number of animals present in the system annually, so relating mortality to stocking pressure on available forage.

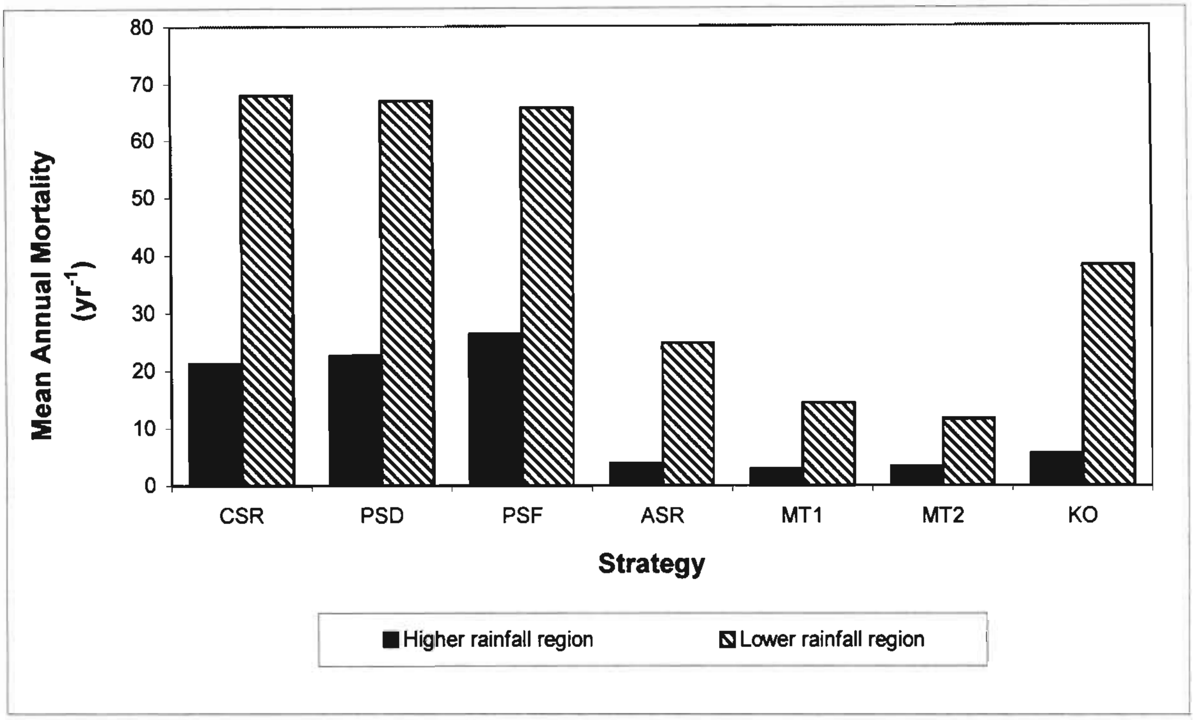

Figure 12: The performance of management strategies in terms of mean annual mortality (yr^{-1}).

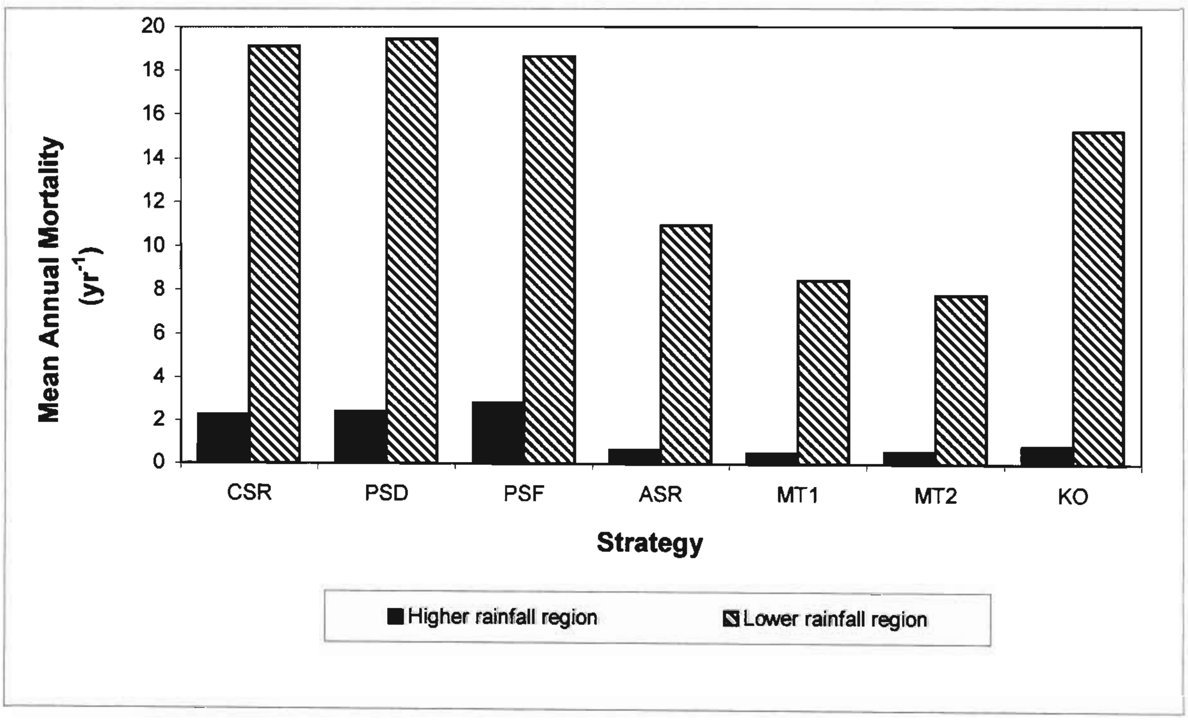

Figure 13: The performance of management strategies in terms of mean annual mortality as a proportion of total animal numbers (yr^{-1}).

4.1.3. *Re-evaluation of management strategies in terms of stocking rates*

The counter-intuitively poor performance of the adaptive stocking rate strategies in comparison with the constant stocking rate and pre-emptive strategies leads to a re-consideration of the method of application of the adaptive stocking rate. In the original comparison of strategy performance in 4.1.2, it was felt that the adaptive stocking rate, governing offtake according to rainfall fluctuations, was not optimising the amount of potential offtake. In addition, the strategies employing the tracking approach were being compared with strategies in which the target stocking level was set to a value which optimised income. The initial analysis in 4.1.2 shows those policies that maintain higher average stocking rates achieving higher income levels and higher annual mortality (see Table 1). Thus, it was decided to incorporate a multiplier into the adaptive stocking rate regression equation that allows the value of the stocking rate obtained from this regression equation to be varied.

With this multiplier in place, a study of the effect of stocking rate on the various model outputs was effected, allowing for a regression relationship between stocking rate and resultant income to be formulated, from which an optimal local stocking rate for each tracking policy was identified. This facilitates a comparison of strategies with each simulated strategy running at its local optimum mean stocking rate.

In addition, in studies carried out by Illius et al. (1998) comparing strategies in terms of offtake in kilograms, the authors note the discrepancies in mean annual stocking rates achieved for the various policies compared and point out the difficulty of isolating the direct effects of the policy in question from the indirect effect of the varying mean annual stocking rate produced by the policy. In their study, these discrepancies are adjusted by means of a covariate analysis, in which model outputs are re-analysed by fitting average annual stocking rate as a covariate and projecting the results for a single standard stocking rate.

In our study, the inclusion of a multiplier in the adaptive regression equation allows for comparisons to be effected in two ways. Firstly, policy outputs are compared for each policy running at its local optimum stocking rate. Secondly, the analysis of the effect of a range of stocking rates produced on policy outputs includes that stocking rate which is directly comparable with the resultant rates produced by the constant and pre-emptive sales policies, which is optimum for these policies and has the value 0.094 $LSE.ha^{-1}$. So the outputs for the adaptive policies resulting from an average annual stocking rate of 0.094 $LSE.ha^{-1}$ are identified and compared with the previous results for the constant and pre-emptive sales policies.

The results for these two comparative studies are illustrated in Figures 14 to 16 below, and Figures 17 and 18 provide a summary of the performance of the constant stocking rate strategy and the average value of the model outputs for the four tracking strategies.

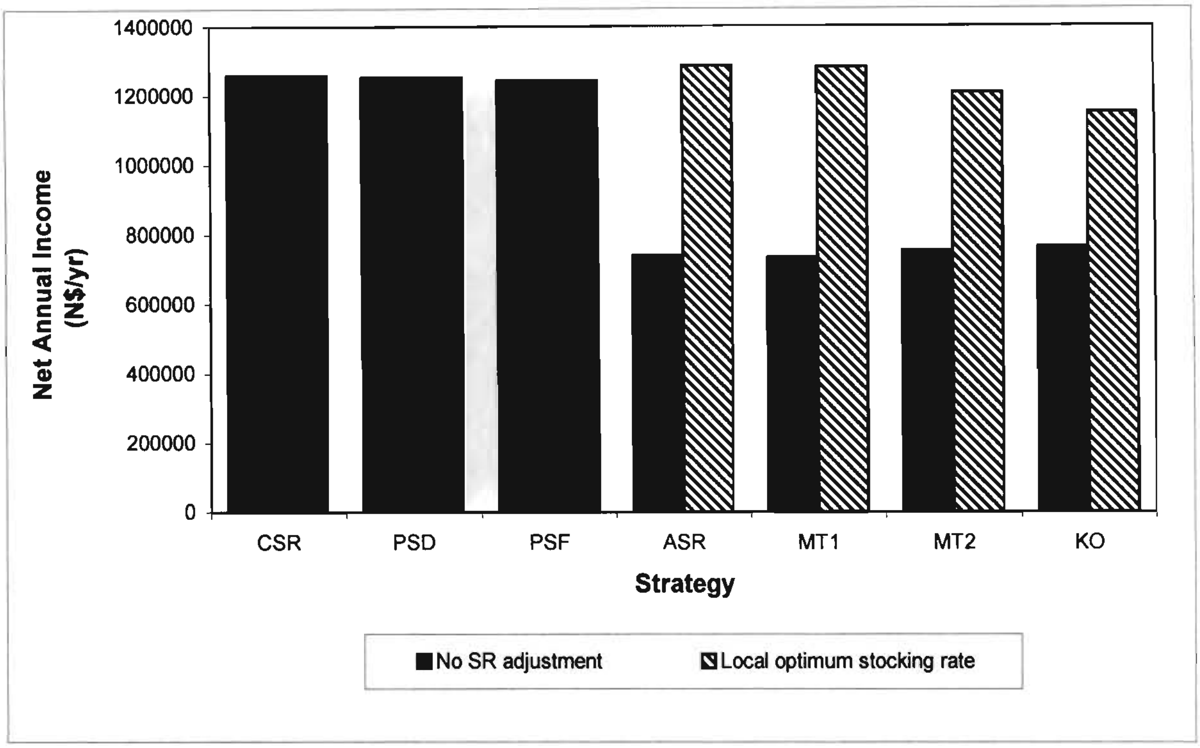

Figure 14: The comparative performance of management strategies in terms of mean net annual income (N$.yr^{-1}) when each strategy is implemented at its local optimum stocking rate by means of an adjustment to the adaptive stocking rate.

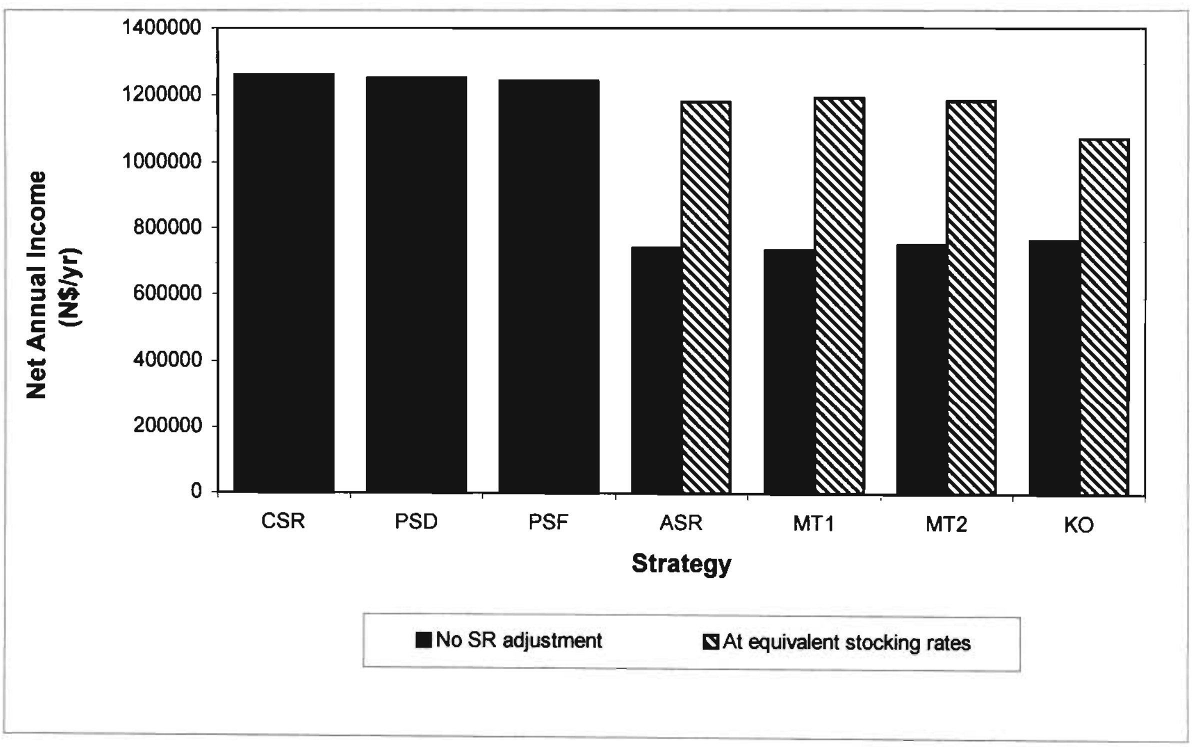

Figure 15: The comparative performance of management strategies in terms of mean net annual income (N$.yr^{-1}) when all strategies are implemented at an equivalent stocking rate by means of an adjustment to the adaptive stocking rate.

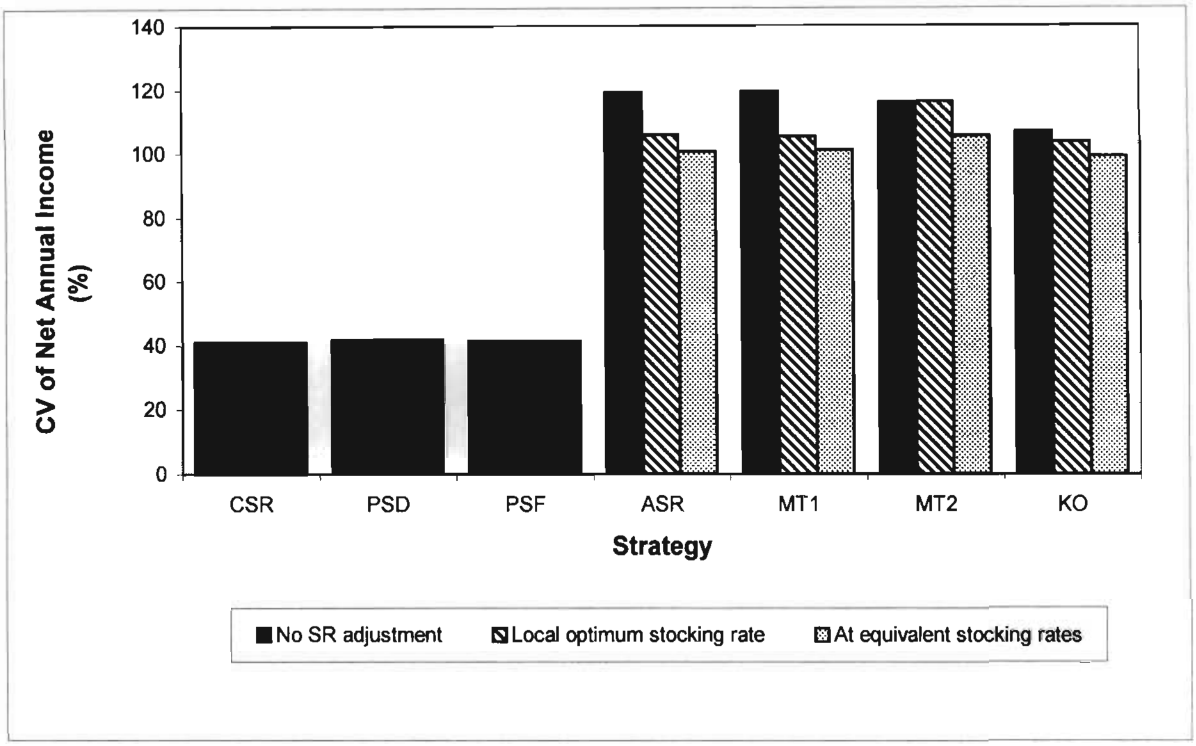

Figure 16: The comparative performance of management strategies in terms of co-efficient of variation of mean net annual income with strategies at both local optimum stocking rates and at equivalent stocking rates.

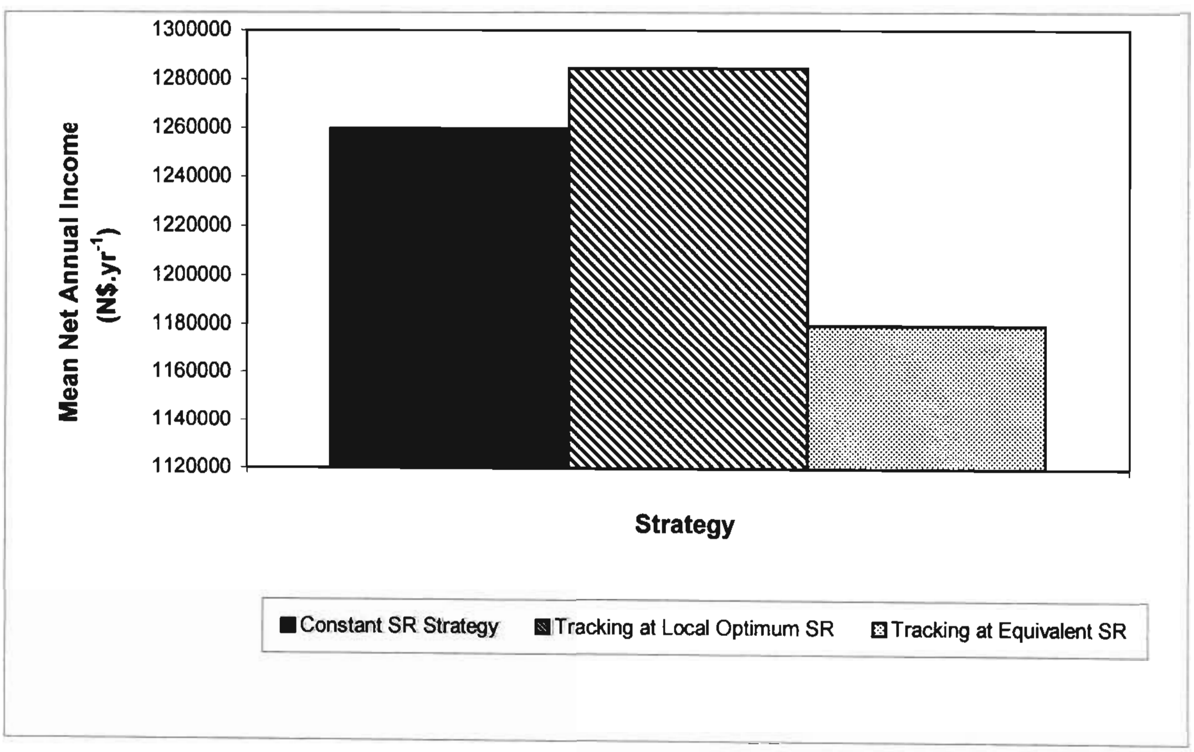

Figure 17: The comparative performance of constant and tracking strategies in terms of mean net annual income (N$.yr^{-1}).

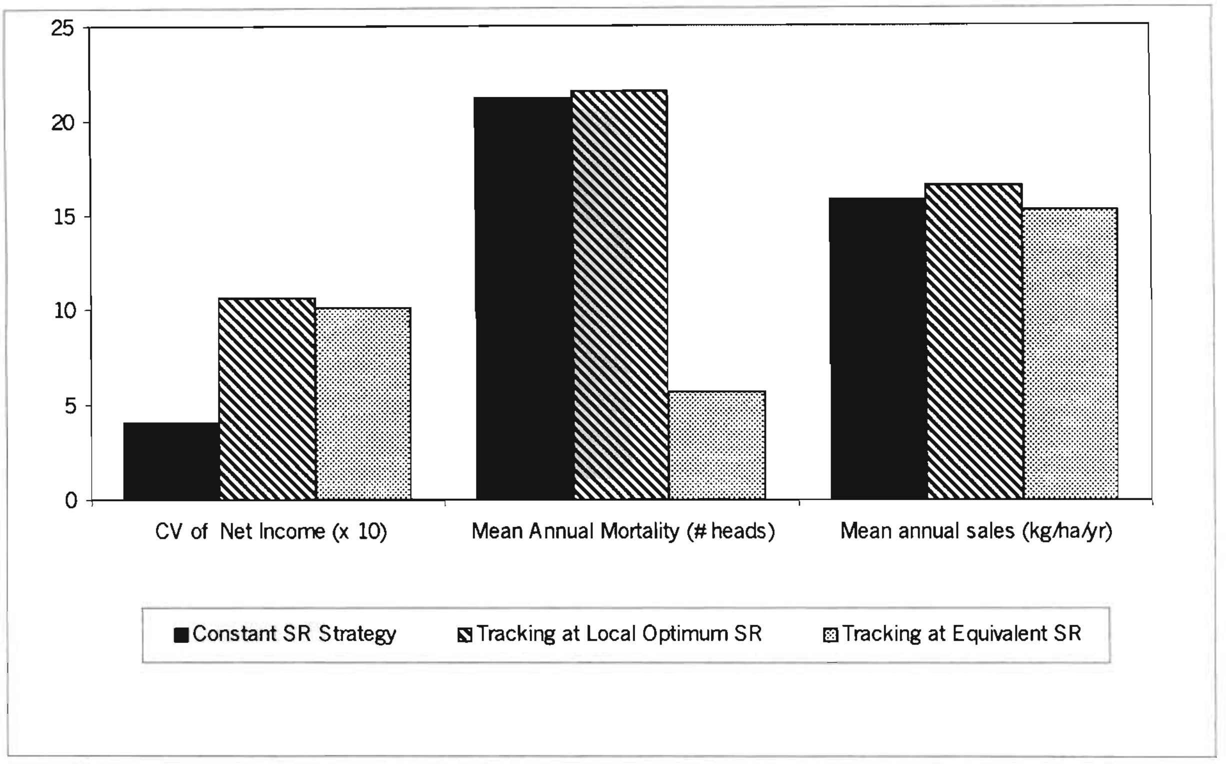

Figure 18: The comparative performance of constant and tracking strategies in terms of co-efficient of variation of mean net annual income (N$.$yr^{-1}$), mean annual mortality (yr^{-1}) and mass offtake ($kg.ha^{-1}.yr^{-1}$).

4.1.4. The influence of offtake order

In removing animals for sale/slaughter, the manager is able to choose the required number of animals in a number of different ways, in terms of age and sex classes. An analysis was performed of the effect of these choices on the economic performance of the strategies and the effect on average annual mortality of various orders of offtake. Order one specifies the removal of oldest to youngest males initially (subject to the minimum sex ratio of bulls to cows required), followed by youngest females to oldest females; this simulates the manager's intention to maintain the breeding herd as far as possible while removing males that are not required for mating. Order two specifies the sale of the youngest male age classes first, followed by the youngest female age classes, then adult males and finally adult females. Order three sees the sales of young adult males and females first, followed by male juveniles and female juveniles, and finally adult males and females.

Figures 19 and 20 below demonstrate the influence of order of offtake on annual income and average annual mortality for the control strategy of applying a constant stocking rate.

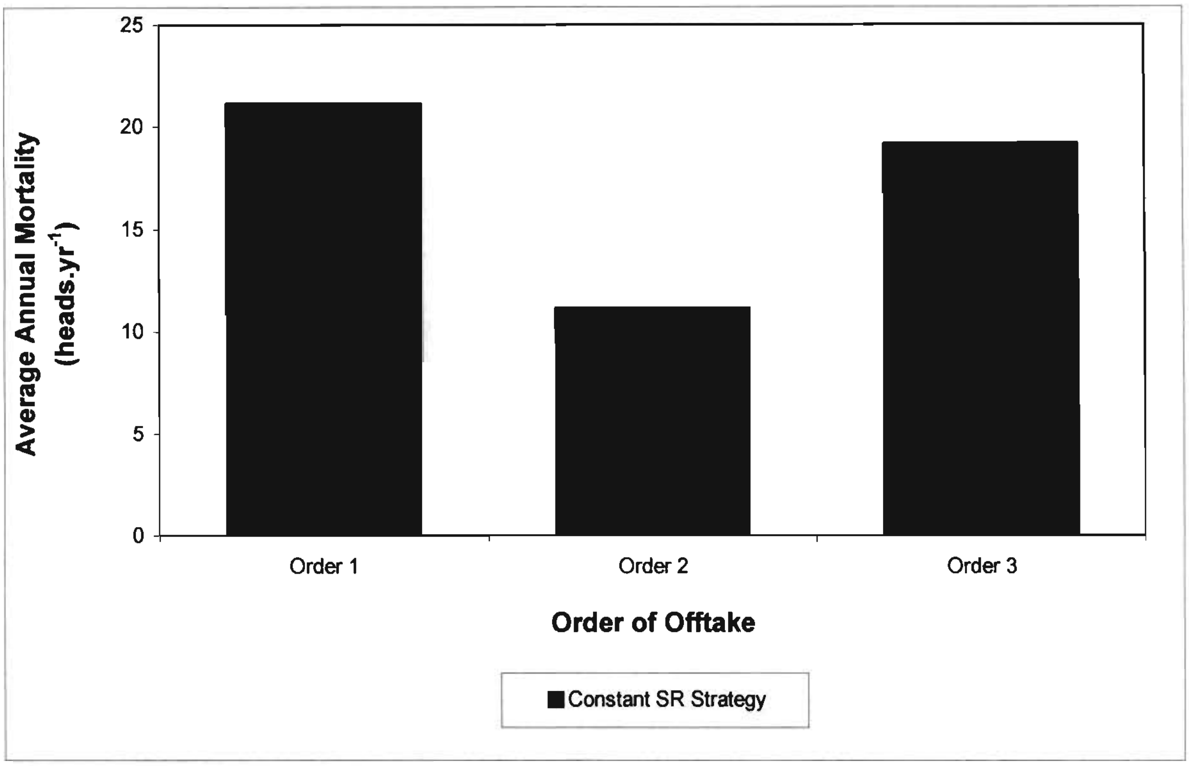

Figure 19: The influence of offtake order on mean net annual income (N\$.yr^{-1}) for the control strategy.

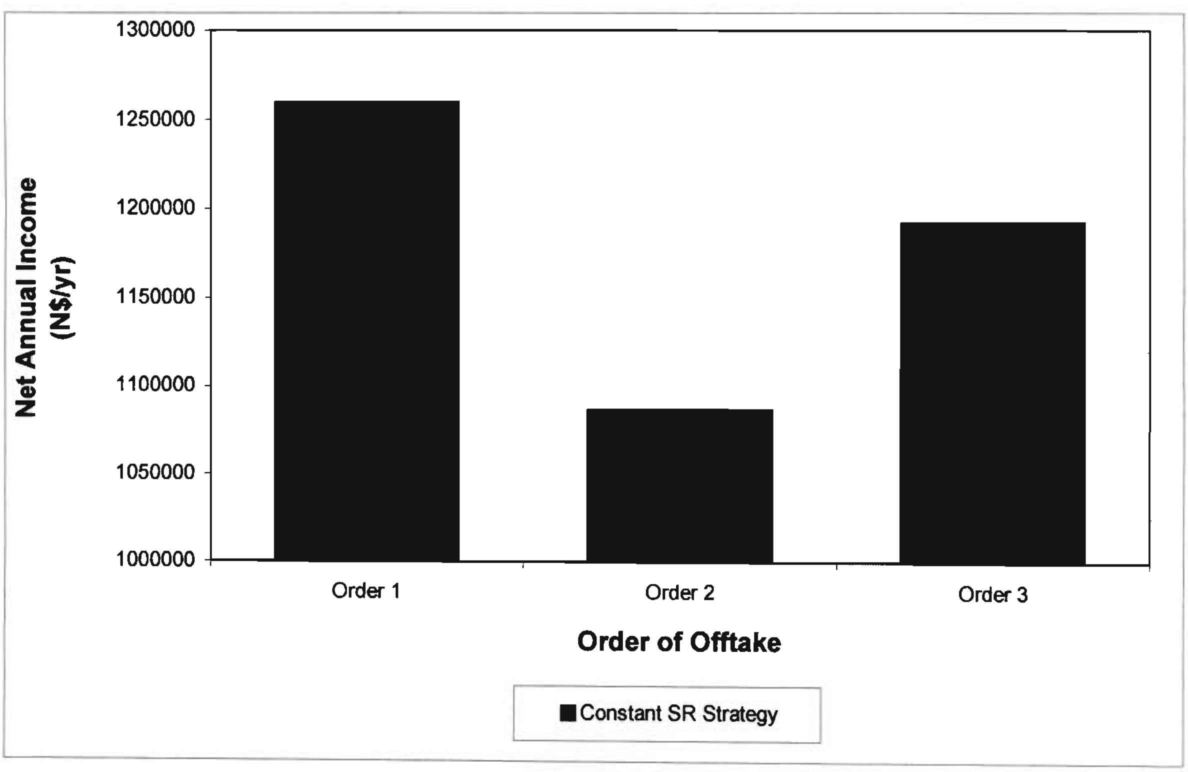

Figure 20: The influence of offtake order on average annual mortality (yr^{-1}) for the control strategy.

4.1.5. Re-visiting the control strategy

Following the analyses described above, it became evident that the tracking strategies were not outperforming other approaches as expected. This lead to a re-evaluation of the manner in which the control strategy was being applied, namely that all stock surplus to the target stocking rate are removed once annually on a specified date, starting with adult males, followed by juvenile males, juvenile females and finally adult females. On closer consideration, this strategy appeared to be rather contrived, and it was felt it did not realistically represent the options available to a manager applying a constant stocking approach. Consequently, it was decided to re-formulate the control strategy to be more rigid and representative of the manager's available options.

According to Gertenbach (*pers. comm.*), the common practise amongst managers is to remove a proportion of those breeding females that do not fall pregnant in any particular breeding season. These animals are referred to as "skips" and this practise seeks to remove females that display a lower-than-average fecundity, thus ensuring that the fecundity rate of the breeding unit remains high (75-80% is considered normal in a well-managed herd). This approach was incorporated into our control strategy, with a specified proportion of "skips" (the rule-of thumb is 20%), choosing the oldest first and moving progressively through the age groups, being removed first ahead of any other herd category to fulfil the annual offtake requirement. This offtake rule is implemented in conjunction with the target stocking rate as before, with a minimum bound on the carcass mass also imposed (the "killing out" threshold), in order to ensure that only animals satisfying a carcass mass requirement of 220 kg form part of the annual offtake. A minor adjustment was made to the "killing out" procedure in that the assessment is made according to the sex of the animal in question; previously, the threshold was specified in terms of a proportion of mature male mass. The adjustment sees thresholds specified separately for males and females in terms of mature male and mature female mass respectively.

Thus, this seeks to simulate the actions of our representative manager more realistically, with the removal of all males that have attained "market" weight excluding those required to maintain a minimum proportion of males to breeding females, all females surplus to herd replacement requirements that have attained "market" weight and "skips" as a proportion of adult female sales: this annual offtake occurs subject to a specified target stocking rate.

Figures 21 and 22 below show the comparative results of the performance of the amended control strategy in comparison with those of the original control strategy and the adaptive tracking strategy.

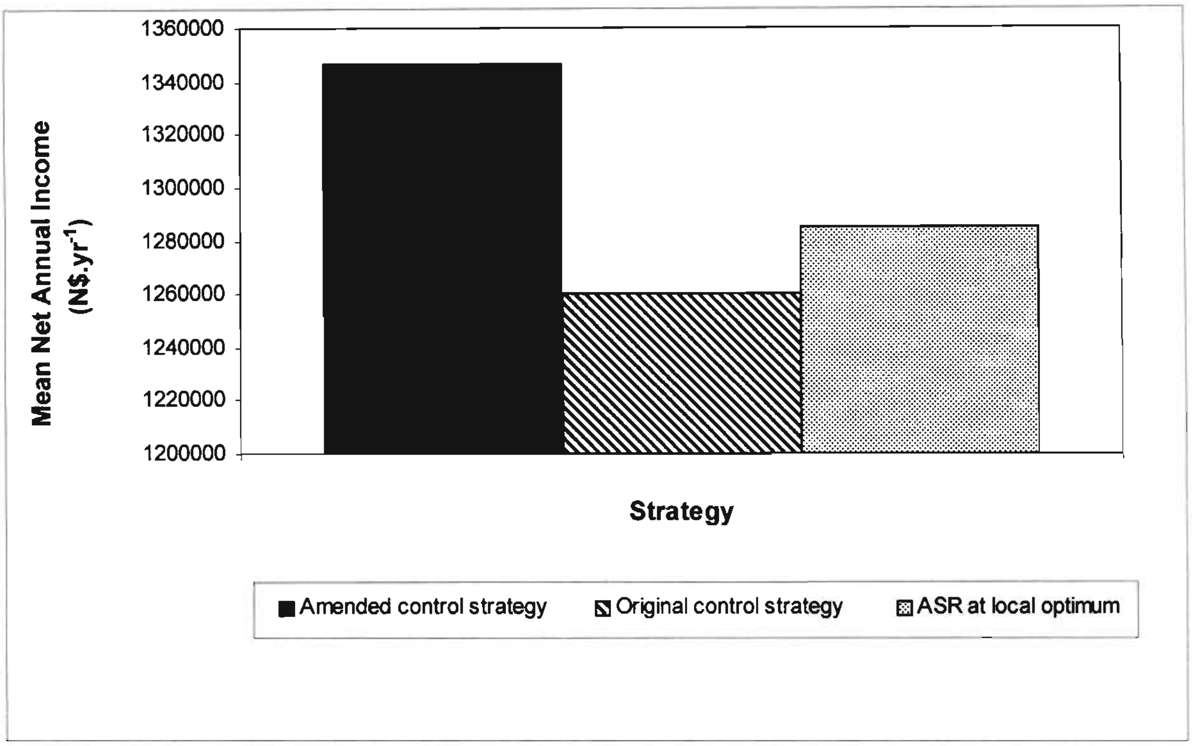

Figure 21: The performance of the amended control strategy in terms of average net annual income (N$.yr^{-1}) compared with that of the original control strategy and the tracking strategy.

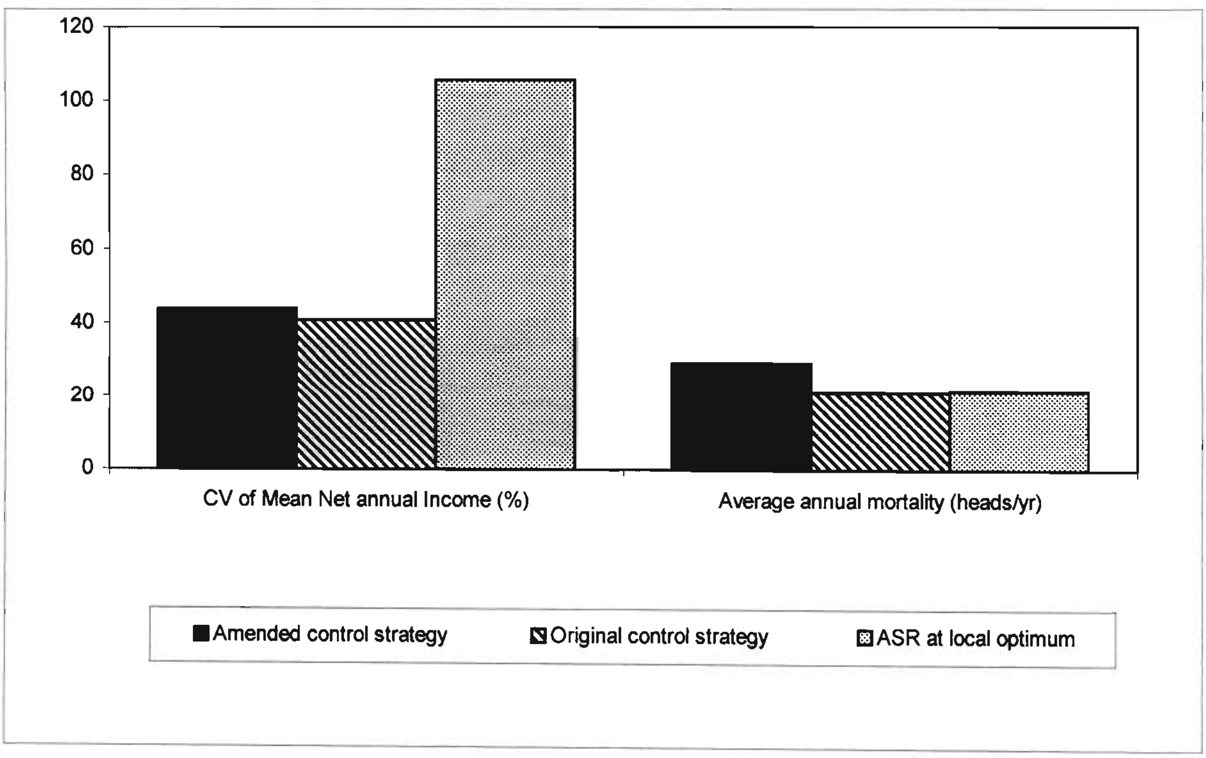

Figure 22: The performance of the amended control strategy in terms of CV of average net annual income and mortality, compared with that of the original control strategy and the tracking strategy.

4.2. DYNAMIC MANAGEMENT

The mechanism governing the dynamic management allows for a variable "offtake month", and a variable decision period (this was set to be the 3 months prior to the default "offtake month") to be specified by management. For each month in the decision horizon ("decision month"), income is calculated for sales in the current month; this is then compared with projected income, calculated according to the expected liveweight gains typical for that month based on average rainfall, and stochastic price fluctuations. Expected liveweight gains are determined according to a linear regression of long-term (20-year simulation) data, relating biomass (fatmass and fat-free mass) for animals in each age class in the current month to the fat mass for the corresponding age class in the subsequent month. This captures the response of liveweight gain to rangeland condition. A mean and co-efficient of variation of monthly prices corresponding to the first decision month allows the prices for the first month of decision to be generated stochastically. These are imposed on the projected liveweight gains to generate incomes that capture variation in market conditions.

Should immediate sales in a given month offer a higher income than projected sales in the decision horizon, then offtake occurs in that month. Otherwise, if it appears that deferring sales will be more lucrative, stock is held over until the following month when the process of comparison between immediate sales and projected sales is repeated, until the specified "offtake day" is reached, when sales surplus to the target stocking rate are effected.

The comparative results of the control strategy, the pre-emptive sales in February strategy and the adaptive stocking rate strategy are shown in Figures 23 and 24 below.

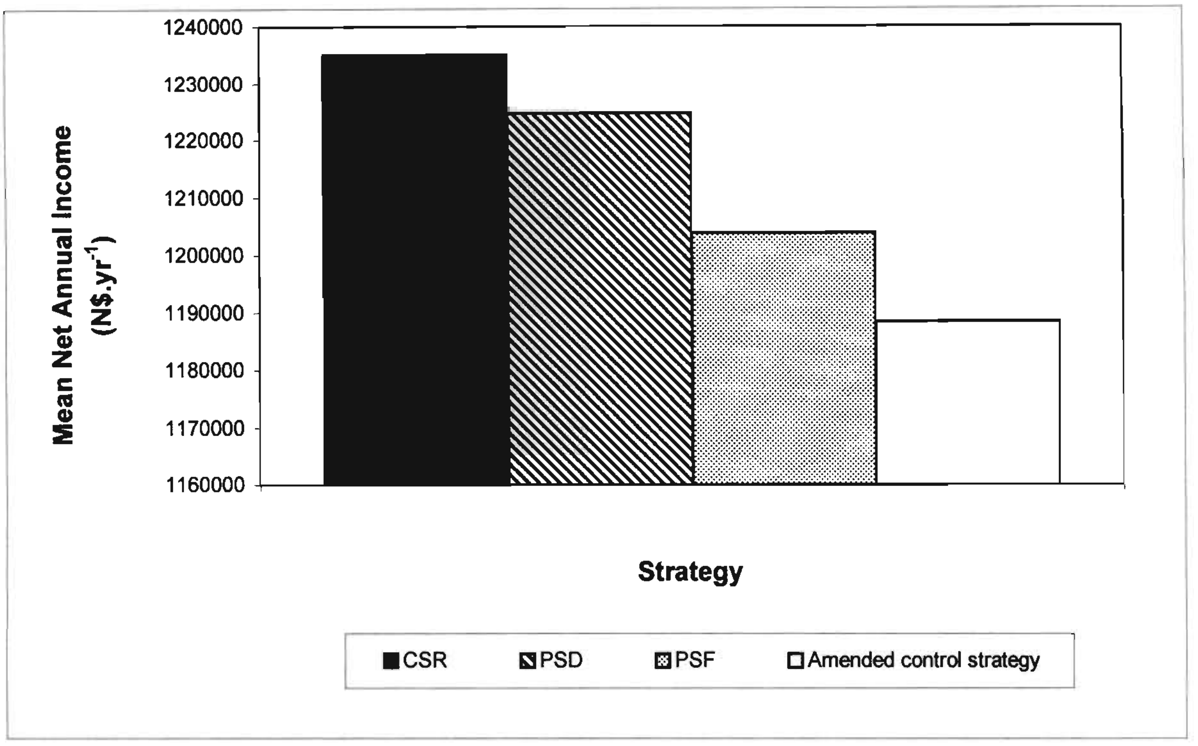

Figure 23: The comparative performance in terms of average net annual income of the constant stocking and pre-emptive sales strategies subject to dynamic feedback effects on decision-making.

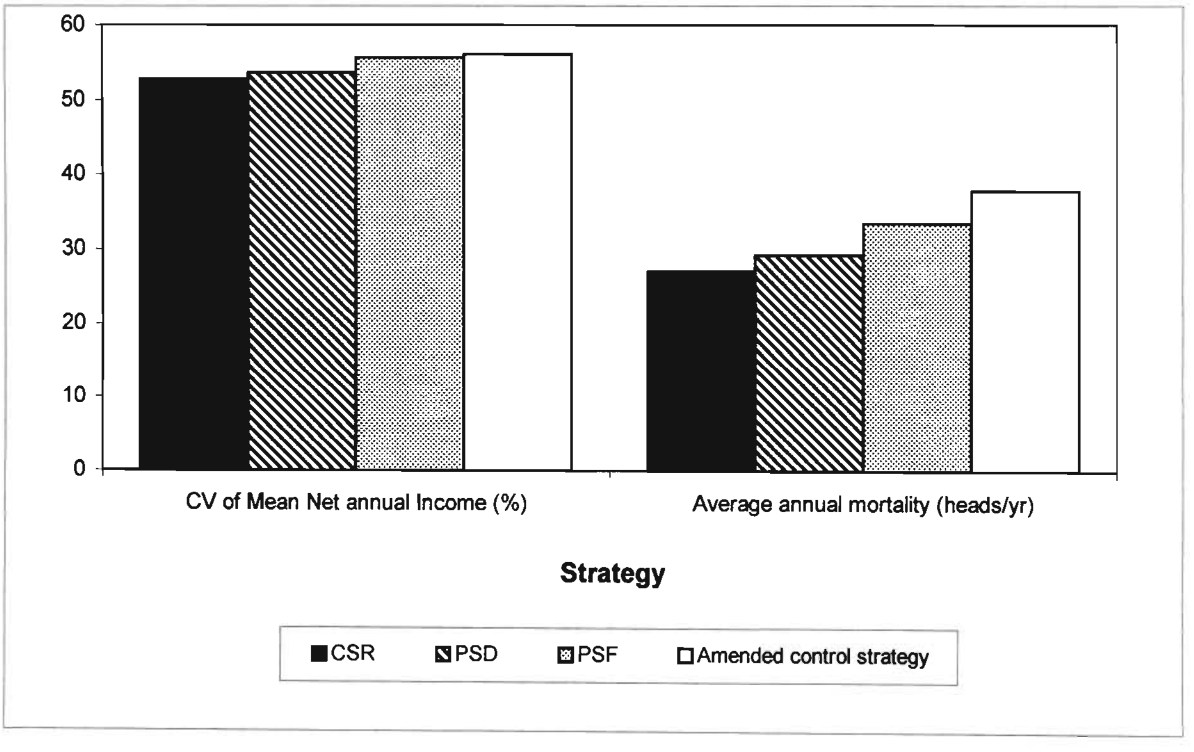

Figure 24: The comparative performance in terms of CV of average net annual income and average annual mortality of the constant stocking and pre-emptive sales strategies subject to dynamic feedback effects on decision-making.

4.3. PRICE ELASTICITY

Economists have coined the term "price elasticity" to describe that characteristic of the functional relationship between two variables that indicates the responsiveness of quantity to price, or vice versa. In agriculture, quantities available for sale are commonly determined by management practices and climatic conditions, and the quantity of the product on the market then "sets the price" at which the quantity is sold (Shepherd, 1963). Conversely, price levels can influence a manager's decision to sell stock in that, should he consider the prevailing price to be low, he might decide to delay sales in the hope of prices improving.

In the preceding analysis, prices are assumed to be inelastic in that prices do not change for fluctuating levels of stock sales. In our model, managers are assumed to be reactive to climatic conditions in their offtake and stocking approaches. This then leads to the argument that if the manager on our representative farm decides to de-stock in the face of anticipated rainfall conditions (be it drought as in the pre-emptive sales strategies or simply prevailing low rainfall as in the adaptive stocking strategies), it is logical to assume that other managers in the region will be implementing the same strategy. Similarly, should rainfall conditions be favourable, managers might hold back stock from sale and take advantage of the availability of grazing, which would lead to a reduction in quantities on the market and an associated increase in price. Given this assumption, the influence of price elasticity comes to bear, since if all farmers are behaving in a similar fashion, there will at times be either a surplus or a shortage of beef on the market, accompanied by corresponding price fluctuations.

The price elasticity of demand is defined as:

$$E_D = \frac{\Delta Q}{\Delta P}\frac{P}{Q} = b_1 \frac{P}{Q} \qquad (20)$$

holding all other factors constant, where

b_1	= $\Delta Q/\Delta P$ is the value of the slope and is negative,
P	= the price of the commodity, and
Q	= the quantity of the commodity.

(Tomek and Robinson, 1972).

Setting the value for E_D and using long-term average values of price and quantity of offtake allows for the construction of an elasticity relation. An elastic price structure is then calculated by applying this relation to the monthly model output of offtake, and new values for the revenues generated by the various management strategies are determined. Nieuwoudt (*pers. comm.*) has estimated the value of the elasticity of demand for the South African beef market to be –0.8. Since the majority of Namibian beef is exported to the South African market (Otto, 1990), it is reasonable to assume that this value can be applied in our Namibian study. However, we also examine other values for E_D as a sensitivity analysis.

An elastic price structure is applied to the offtake simulation output for the amended control strategy and the adaptive stocking strategy at its local optimum. The results for various elasticity values are depicted in Figures 25 and 26 below.

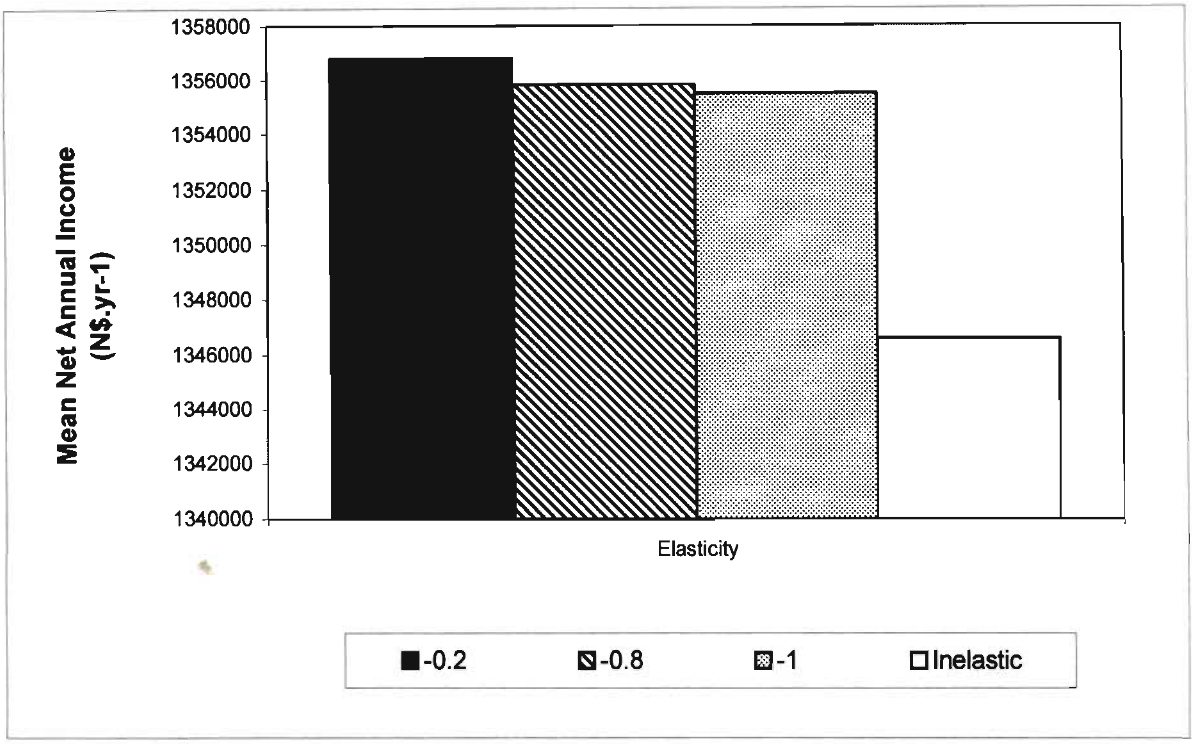

Figure 25: The effect of an elastic price structure on the average annual income (N$.yr^{-1}) of the amended control strategy.

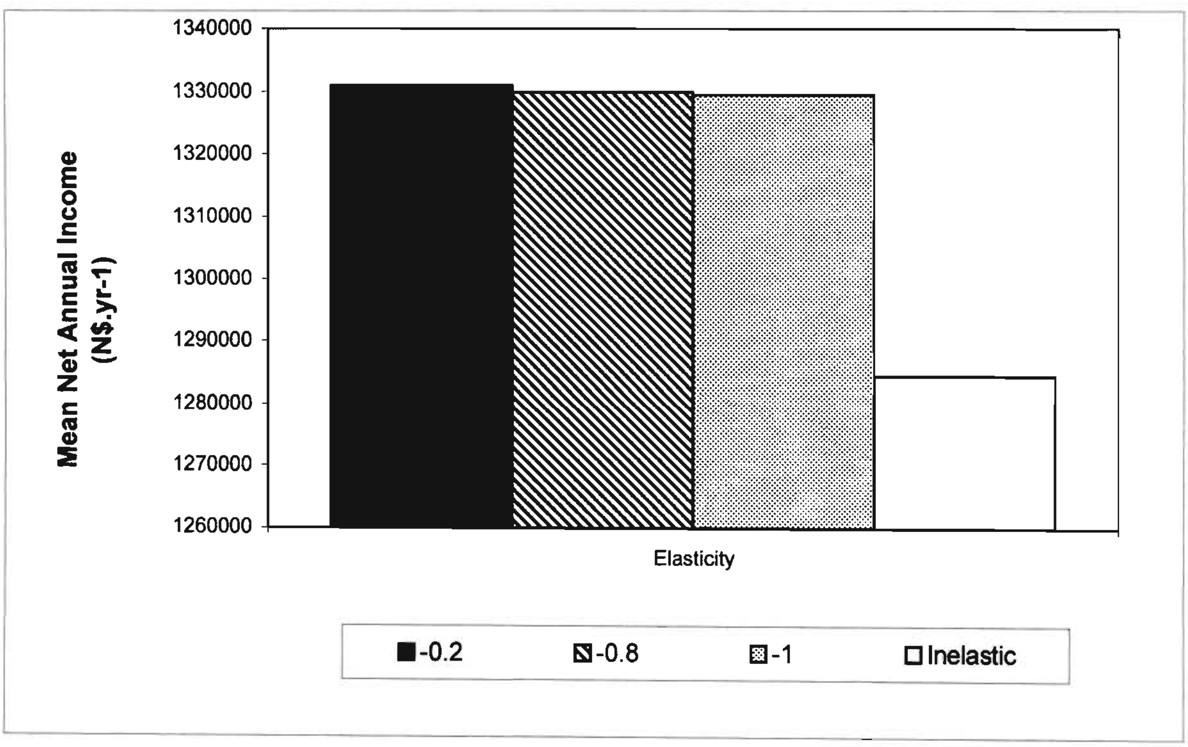

Figure 26: The effect of an elastic price structure on the average annual income (N$.yr^{-1}) of the adaptive stocking strategy at its local optimum.

Table 1 below summarises the model outputs for the various strategies and their resultant mean annual stocking rates.

	Strategy	Average Annual Stocking Rate ($LSE.ha^{-1}$)	Mean Net Annual Income ($N\$.yr^{-1}$)	CV of Mean Net Annual Income (%)	Mean Annual Mortality (yr^{-1})
Initial Results with no adjustment of the adaptive stocking rate	CSR	0.094	1259768.69	40.89	21.2
	PSD	0.094	1250968.77	41.70	22.6
	PSF	0.093	1242802.48	41.43	26.3
	ASR	0.059	738920.97	119.08	3.9
	MT1	0.059	733753.36	119.39	2.9
	MT2	0.059	751233.30	115.98	3.3
	KO	0.066	763730.48	106.74	5.5
All strategies achieving their local optimum stocking rate	CSR	0.094	1259768.69	40.89	21.2
	PSD	0.094	1250968.77	41.70	22.6
	PSF	0.093	1242802.48	41.43	26.3
	ASR	0.106	1284541.22	105.72	21.58
	MT1	0.105	1281392.33	105.08	20.01
	MT2	0.097	1206187.94	116.09	15.18
	KO	0.100	1147779.54	103.47	22.20
All strategies achieving equivalent mean annual stocking rates	CSR	0.094	1259768.69	40.89	21.2
	PSD		1250968.77	41.70	22.6
	PSF		1242802.48	41.43	26.3
	ASR		1179869.76	100.48	5.65
	MT1		1191748.02	100.89	4.18
	MT2		1183237.24	105.23	7.50
	KO		1070997.66	98.87	15.08
	Amended Control Strategy (ACS)	0.094	1346583.48	43.74	29.4
Dynamic management	CSR	0.095	1235006.80	52.74	27.0
	PSD	0.095	1224640.13	53.64	29.3
	PSF	0.095	1203813.71	55.59	33.48
	ACS	0.097	1188348.38	56.03	37.84

Table 1: Summary of results.

Table 2 summarises the results of the Analysis of Variation between strategies for the associated model output.

Model Output	SR description	5% level of significance	1% level of significance
Mean annual mortality	No adjustment	Significant	Significant
	Equivalent SR's	Significant	Significant
	Local optimum SR	Not Significant	Not Significant
CV of Mean annual mortality	No adjustment	Significant	Significant
	Equivalent SR's	Not Significant	Not Significant
	Local optimum SR	Not Significant	Not Significant
Mean net annual income	No adjustment	Significant	Significant
	Equivalent SR's	Significant	Significant
	Local optimum SR	Not Significant	Not Significant
CV of Net annual income	No adjustment	Significant	Significant
	Equivalent SR's	Significant	Significant
	Local optimum SR	Significant	Significant
Mean annual sales (kg/ha/yr offtake)	No adjustment	Significant	Significant
	Equivalent SR's	Significant	Significant
	Local optimum SR	Not Significant	Not Significant
CV of Mean annual sales	No adjustment	Significant	Significant
	Equivalent SR's	Significant	Significant
	Local optimum SR	Significant	Significant

Table 2: Summary of the significant differences between strategies at the 1% and 5% level.

4.4. DISCUSSION OF RESULTS

From the simulation results, depicted graphically in the preceding sections of this chapter, the following observations can be made:

- Preliminary investigation revealed the influence of rainfall sequence on the vegetation and herbivore dynamics, and the sensitivity of simulation results to the input sequence of rainfall years. This was in concurrence with the findings of Stafford Smith et al. (1996). To avert this effect, a fully replicated design of randomly generated rainfall sequences was adopted, which was then employed for all simulations. Model outputs were averaged over this set of replicates.

- Preliminary results revealed that constant stocking rate and pre-emptive sales management tactics performed, on average, about 40% better than the various strategies employing an adaptive stocking rate, with little difference observed between the two categories of strategies. This result was felt to be counter-intuitive, and must be viewed in the light of the lower average annual stocking levels achieved by the adaptive stocking policies. It is not possible to isolate the effect of the individual strategy from the influence of the average stocking level that it achieves. However, it is noted by Stafford Smith and Foran (1991) that higher stocking rates do not necessarily always generate more revenue than lower stocking rates. It is the stocking level that ensures maximum productivity per hectare that is optimum. The disparity between the various stocking rates achieved by the simulated strategies encouraged further investigation.

- In contrast to widely-accepted economic theory, the higher economic returns are associated with higher risk, our results indicate that the strategies that perform the best in terms of revenue generated, namely the constant stocking and pre-emptive sales options, also perform better than the sub-set of tracking strategies in terms of variability of income, which is viewed as a measure of risk. In fact, the tracking scenarios are characterised by a variability of income that is more than double that of the constant and pre-emptive approaches.

- The adaptive stocking options are successful in reducing average annual drought-related mortality, as a proportion of the total herd, to almost half that produced by the constant and pre-emptive strategies. Indeed, tracking mortality and removing a specified number of animals for each starvation-related death is more effective on this regard than the purely adaptive stocking approach, as would be expected.

- Implementing each strategy at its local optimum average stocking rate sees the subset of tracking strategies marginally outperforming the control strategy and the pre-emptive sales strategies in terms of average net annual income, as well as a slight reduction in the co-efficient of variation of average net annual income.

- Implementing each strategy at a single resultant average stocking rate of 0.094 LSE.ha^{-1} also improves the performance of the adaptive stocking strategies, and sees them generating nearly the same returns as the control and pre-emptive sales policies. Variability of income is also slightly reduced, and average annual mortality is markedly reduced.

- Order of offtake has an effect on average annual mortality and the average net annual income for the control policy.

- The amended control strategy shows an improved performance over the original control strategy and the adaptive stocking strategy in terms of income. Variability of income and mortality are slightly higher for the former in comparison to the original control strategy, but not significantly so.

- Incorporating a dynamic feedback mechanism that governs the decision to remove stock subject to a constant target stocking level has the effect of reducing average annual income and increasing variability of income, particularly for the amended control strategy. A slight increase in mortality also results for all strategies.

- Application of an elastic price structure increases average annual income for the amended control strategy marginally (approximately 1%) and improves average annual income for the adaptive stocking strategy by approximately 4% over the performance corresponding to an inelastic price structure.

4.4.1. Comments

The overall performance of constant and pre-emptive sales management approaches is better than that of the tracking options in terms of revenue generated and variability of income. Within the subset of constant stocking management, results indicate that removing stock pre-emptively in the face of lower than average rainfall conditions does not substantially affect revenues generated. Thus, it appears to be inconsequential whether stock is removed in December, February or March – however, later removal as in the adaptive stocking policies reduces revenue. So timing of offtake is shown to be crucial, and such offtake should be effected before the start of the dry winter season. By the time rainfall conditions are at their lowest ebb, animals have already lost condition and loss of potential revenue is compounded by the lower beef prices typical of the winter season. As expected, order of offtake also plays a role in the income generated and the average annual mortality of the control strategy. Since order one is the most realistic approach to removal of stock in that it is practised by livestock managers, and also produces the best mean annual returns, this is the order that was used in all simulations.

Although tracking is effective in reducing annual stock mortality, it appears the constant stocking level strategies (including the pre-emptive sales) provide a more consistent annual income in not being responsive to fluctuating rainfall conditions, and that the utilisation of the available resources and forage associated with the given climatic conditions is effective and sustainable. It is clear that optimal target stocking rate implemented for the constant stocking strategies is one that the system is able to support, without dramatic population crashes or depletion of forage resources. The removal of animals in response to drought-related mortality in conjunction with an adaptive stocking level does not improve the returns corresponding to this strategy. This is a result of the much reduced mortality that arises from an adaptive stocking approach, so the limited number of animals that would be removed by mortality tracking are not sufficient to markedly affect revenue, although this approach is effective in reducing mortality further. Indeed, it appears that the adaptive approach pre-empts starvation as a consequence of drought, by removing stock timeously.

Applying each strategy at its local optimum average stocking rate is successful in improving the performance of the tracking strategies, both in terms of average annual net income and variability of this income. In fact, this approach has the effect that the basic tracking strategy now generates more income than the control strategy of a constant stocking level. Ensuring that each strategy ultimately achieves a single average long-term stocking level allows the effect of stocking level on the performance of each strategy to be removed and facilitates a direct comparison of performance. In this case, we see that the incomes generated are more comparable, with the control strategy and pre-emptive sales doing marginally better than the tracking strategies, although there is little to choose between the two categories in terms of income. In fact, the results suggest that there is no significant difference between strategies when they are compared at an equivalent stocking rate. This is in keeping with the findings of Illius et al. (1998), although the method of comparison at equivalent stocking rates differs. It is now the variability of income and average annual mortality that become the dominant factors; an individual manager's choice of strategy would hinge on these factors depending on his personal risk preference.

The amended control strategy improves on the performance of the original control strategy and the basic tracking strategy by approximately 7% and 5% respectively. This effect is largely due to the fact that the removal of non-productive females generates income without depleting herd productivity, since these females are not contributing towards productivity in any event. In addition, the minimum carcass mass requirement implies that offtake that occurs is biased towards older animals in better condition, as opposed to the random nature of selection for offtake of the original control strategy, thus increasing revenue.

Applying a decision rule governing offtake based on forecasting potential income and then comparing it with income that could be realised immediately does not improve the economic performance of the constant stocking, pre-emptive sales and the amended control strategy. These results suggest that the greatest economic benefit to be derived is from sales immediately prior to the onset of the dry winter season, which is the approach implemented by the control policy.

Selling stock prior to this does not offer economic benefit on average. This indicates that it is better to delay offtake till this point and allow stock to gain weight from foraging on the available resources. It appears that these resources are sufficient to sustain the herd without loss of condition.

An analysis involving pairwise comparisons of the model outputs for the various strategies was performed using the Tukeys method of pairwise comparisons. This method compares the means of each strategy output: the null hypothesis assumes the difference between the two means being compared to be zero. Confidence intervals are established, with acceptance of the null hypothesis if the difference between the two means falls within the limits of the confidence interval (Groebner and Shannon, 1987). The results are summarised in tabular form in Appendix 2, and the differences in terms of average net annual income are discussed briefly below.

Differences between management strategies in terms of average net annual income

- With no SR adjustment: Highly significant differences are observed when comparisons are drawn with reference to the variable "mean net annual income" among the levels of strategy. These occur when the constant and pre-emptive strategies are compared to the tracking strategies. No significant difference is observed within the constant and pre-emptive strategy groups; likewise the various tracking strategies, when compared with one another are deemed not to be significantly different.

- At equivalent stocking rates: With all strategies at comparable mean resultant stocking rates, comparisons between constant, pre-emptive and tracking strategies show that there is no significant difference between the various management approaches with one exception. This is for the "Killing Out" strategy, which demonstrates a highly significant difference from the tracking and pre-emptive strategies, and a significant difference from the other tracking strategies. In fact, results show that this strategy demonstrates markedly lower economic returns than the other strategies investigated.

- At local optimum stocking rates: When all strategies are implemented at their local optimum stocking rates, there is no significant difference between the constant, pre-emptive and tracking strategies with the exception once again of the "Killing out" strategy. Results of the analysis reflect a significant difference between this strategy and the ASR and MT1 strategies.

The results presented above, along with salient points from this discussion, are summarised in Chapter Five.

CHAPTER FIVE

CONCLUSION

In the light of the ongoing debate concerning the effectiveness of "tracking" as opposed to the implementation of a constant stocking, the primary objective of this study was to examine the performance of various management strategies incorporating these approaches in terms of their economic viability, measured both in terms of revenue generated and risk level as indicated by the variability of income. To this end, a stochastic, rainfall-driven plant-herbivore simulation model was adapted for regional implementation in Namibia and an economic component was added to this model, incorporating a seasonal price structure and a mechanism for assessing the effect of forecasting potential income on offtake decision-making. Simulations of the various management strategies proposed allowed for a ranking of strategies in terms of various model outputs.

The investigations carried out in this research indicated that the tracking approaches implemented were unsuccessful in improving the economic performance of the livestock production system modelled, both in terms of annual income generated and the variability of this income. However, employing an adaptive stocking level in response to prevailing rainfall conditions allowed for a substantial reduction in stock mortality. It is clear that the influence of seasonal price variation does play some role in the poorer returns characterising the tracking approach, since, by their design, tracking strategies trigger offtake primarily throughout the dry winter season, and during drought conditions. Prices are historically lower during the winter months, and compounding this effect is the fact that animals have already begun to lose condition due to a reduction in available forage resources, thus fetching lower prices.

Results indicate that pre-emptive offtake in response to lower-than-average rainfall during the rainfall season does not markedly affect revenues generated by applying a constant stocking level. This is indicative that a short-term response such as this has little value, since the control strategy removes stock surplus to the target level in mid-March, before the onset of the dry season, while forage is still available, allowing animals to maintain satisfactory body weight. However, timing of offtake in the longer term was found to be influential, with offtake later in the grazing season negatively affecting returns. Similarly, the implementation of "mortality tracking" in conjunction with an adaptive stocking level did not improve returns in comparison to simply applying an adaptive approach. In addition, the performance of the various strategies was found to sensitive to the specified order of offtake i.e. the order of priority of removal from specific age and sex classes. However, the order providing the best performance was that which was considered to be the most realistic, namely the removal of oldest to youngest males followed by youngest to oldest females.

It is clear from the results that income is sensitive to the long-term average stocking level resulting from a particular management approach. Removing the effect of stocking level by comparing strategies at the same stocking level indicated that tracking does not perform comparatively as poorly as the initial results suggested. Indeed, this comparison showed there to be little difference in revenues achieved by the constant stocking and tracking approaches. Furthermore, when each individual strategy was implemented at its local optimum stocking level, tracking strategies generated higher income than the control strategy, albeit a small margin of difference. As is to be expected, the model outputs showed the system to be negatively affected by target stocking rates that were too high, while those that were low also produced a reduction in revenue. The target stocking rates chosen for the constant stocking strategies were ones that the system, with its given climatic inputs, was obviously able to support without experiencing population instability and unrecoverable mortality during drought situations. It is felt that this contributed to the comparatively successful performance of a constant stocking approach.

The application of a more realistic control strategy that encompasses limitations on carcass mass and enforces removal of non-breeding females resulted in a further improvement in income without any significant increase in variability of income or annual mortality. This was the result of the additional income generated by the removal of non-breeding females, as these animals make no contribution to herd production and so their removal has no negative effect on productivity.

The incorporation of a dynamic feedback component to allow for projected income to be estimated and this estimation used to govern offtake decisions was found to be ineffective in improving the performance of the various strategies simulated.

In overview, this research indicates that there is little value to be gained in the implementation of complicated tracking rules to govern stock offtake in a livestock production system in highly variable climates. Application of a constant stocking rate that adheres to a chosen target level shows itself to be the management option that provides the best returns and lowest variability in income, subject to this target level being one that allows the system to support sustainable production levels for a given climatic regime.

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APPENDIX 1: ADDITIONAL EQUATIONS UNDERLYING THE SimSAGS MODEL

Animal Intake Equations

Incisor arcade breadth is a measure of the morphology of the animal's mouth and is a factor governing bite mass, which in turn regulates herbivore intake. Illius and Gordon (1987) use the equation:

$$I_B = aM^{0.245} \qquad (21)$$

where:

I_B = the incisor arcade breadth (mm),

a = a species-specific parameter accounting for size, and

M = the individual's body mass (kg).

Bite rate is also used in determining animal intake. Illius and Gordon (1998) modified the equations of Spalinger and Hobbs (1992) which describe three processes that limit intake rate. These are namely rate of encounter with different types of forage, these being those that can only be detected at close range (possibly obscured), those that can be detected from a distance (Process 1 and 2 respectively) and rate of chewing and swallowing in the case where bite mass is sufficiently large that chewing rate is the limiting factor on intake (Process 3). The equations follow:

$$B_1 = \frac{V_{max}\, wD}{1 + nV_{max}\, wD} \qquad \text{(Process 1)} \qquad (22)$$

$$B_2 = \frac{V_{max}\sqrt{D}}{1 + nV_{max}\sqrt{D}} \qquad \text{(Process 2)} \qquad (23)$$

$$B_3 = \frac{R_{max}}{S + R_{max} h} \qquad \text{(Process 3)} \qquad (24)$$

where

B_i = bite rate for process i (i = 1,2,3),

V_{max} = maximum foraging velocity (m.s^{-1}),

R_{max} = maximum eating rate (kg.s^{-1}),

w = width of search park (m),

D = bite density (m^{-2}),

n = parameter governing time lost to future potential intake while stopping to take a bite (s),

S = bite mass (kg), and

h = minimum handling time per bite in the absence of chewing (s).

Energy balance equations

Net energy expenditure is calculated as the sum of the basic requirements of the animal (basal or fasting metabolism), the energy expended whilst grazing for intake and digestion (which is related to the grazing time and the mass of the animal), the energy expended by moving whilst grazing, and the energy expended whilst commuting between grazing sites. So net energy expenditure is formulated as:

$$E_{exp} = FM + E_{graze} + E_{mov} + E_{com} \qquad (25)$$

where

E_{exp} = net metabolisable energy expended (MJ.day^{-1}),

FM = fasting metabolism (MJ.day^{-1}),

E_{graze} = energy expended whilst grazing (MJ.day^{-1}),

E_{mov} = energy expended by moving whilst grazing ($MJ.day^{-1}$), and

E_{com} = energy expended by commuting between grazing sites ($MJ.day^{-1}$).

(Koch, 1999).

Illius and Gordon (1998) relate fasting metabolism to animal mass by the following equation:

$$FM = 0.3 * M * A^{-0.27} \qquad (26)$$

where

A = the mature mass of the animal (kg), and

M = the actual mass of the animal (kg).

Energy expenditure on foraging includes energy costs for maintenance of posture ($J.s^{-1}$), travel ($J.m^{-1}$) and grazing ($J.s^{-1}$). Illius and Derry (*pers. comm.*) and Koch (1999) formulate the following equations to describe E_{graze}, E_{mov} and E_{com}:

$$E_{graze} = \frac{0.0029 * GT * M}{60 * 60} \qquad (27)$$

where

GT = grazing time (s).

Energy expended by moving whilst feeding is:

$$E_{mov} = \frac{GT * 0.748 * M^{0.735} + 15.8 * M^{0.589} * F_{dist}}{1000000} \qquad (28)$$

where

F_{dist} = distance moved while feeding (m).

Energy expended while commuting between grazing sites is given by:

$$E_{com} = \frac{CT * 0.748 * M^{0.735} + 15.8 * M^{0.589} * C_{dist}}{1000000} \qquad (29)$$

$$CT = \frac{C_{dist}}{COMVEL} \quad (30)$$

$$COMVEL = 0.33 * A^{0.21} \quad (31)$$

where

CT = time spent commuting (s),

C_{dist} = distance travelled while commuting (m), and

$COMVEL$ = velocity at which animal commutes ($m.s^{-1}$).

APPENDIX 2: TESTING SIGNIFICANT DIFFERENCES BETWEEN MODEL OUTPUTS ASSOCIATED WITH MANAGEMENT STRATEGIES

Note: n.s. denotes "not significant", * denotes significance at the 5% level and ** denotes significance at the 1% level.

Income	Strategy	CSR	PSD	PSF	ASR	MT1	MT2	KO
With no SR adjustment	CSR		1.000	0.9981	0.0000	0.0000	0.0000	0.0000
	PSD	n.s.		1.0000	0.0000	0.0000	0.0000	0.0000
	PSF	n.s.	n.s.		0.0000	0.0000	0.0000	0.0000
	ASR	**	**	**		1.0000	0.9997	0.9853
	MT1	**	**	**	n.s.		0.9978	0.9619
	MT2	**	**	**	n.s.	n.s.		0.9997
	KO	**	**	**	n.s.	n.s.	n.s.	
With strategies at an equivalent SR	CSR		1.0000	0.9992	0.2984	0.4968	0.3500	0.0000
	PSD	n.s.		1.0000	0.4415	0.6581	0.5020	0.0001
	PSF	n.s.	n.s.		0.5904	0.7942	0.6519	0.0001
	ASR	n.s.	n.s.	n.s.		0.9999	1.0000	0.0487
	MT1	n.s.	n.s.	n.s.	n.s.		1.0000	0.0189
	MT2	n.s.	n.s.	n.s.	n.s.	n.s.		0.0377
	KO	**	**	**	*	*	*	
With strategies at their local optimum SR	CSR		1.0000	0.9996	0.9967	0.9985	0.8523	0.1052
	PSD	n.s.		1.0000	0.9833	0.9900	0.9318	0.1703
	PSF	n.s.	n.s.		0.9508	0.9663	0.9740	0.2535
	ASR	n.s.	n.s.	n.s.		1.0000	0.4873	0.0208
	MT1	n.s.	n.s.	n.s.	n.s.		0.5377	0.0261
	MT2	n.s.	n.s.	n.s.	n.s.	n.s.		0.7936
	KO	n.s.	n.s.	n.s.	*	*	n.s.	

Table 3: Pairwise comparisons of management strategies in terms of mean net annual income.

Income	Strategy	CSR	PSD	PSF	ASR	MT1	MT2	KO
With no SR adjustment	CSR		1.0000	1.0000	0.0000	0.0000	0.0000	0.0000
	PSD	n.s.		1.0000	0.0000	0.0000	0.0000	0.0000
	PSF	n.s.	n.s.		0.0000	0.0000	0.0000	0.0000
	ASR	**	**	**		1.0000	0.9777	0.0146
	MT1	**	**	**	n.s.		0.9638	0.0111
	MT2	**	**	**	n.s.	n.s.		0.1469
	KO	**	**	**	*	*	n.s.	
With strategies at an equivalent SR	CSR		1.0000	1.0000	0.0000	0.0000	0.0000	0.0000
	PSD	n.s.		1.0000	0.0000	0.0000	0.0000	0.0000
	PSF	n.s.	n.s.		0.0000	0.0000	0.0000	0.0000
	ASR	**	**	**		1.0000	0.8222	0.9992
	MT1	**	**	**	n.s.		0.8760	0.9973
	MT2	**	**	**	n.s.	n.s.		0.5361
	KO	**	**	**	n.s.	n.s.	n.s.	
With strategies at their local optimum SR	CSR		1.0000	1.0000	0.0000	0.0000	0.0000	0.0000
	PSD	n.s.		1.0000	0.0000	0.0000	0.0000	0.0000
	PSF	n.s.	n.s.		0.0000	0.0000	0.0000	0.0000
	ASR	**	**	**		1.0000	0.1084	0.9971
	MT1	**	**	**	n.s.		0.0720	0.9996
	MT2	**	**	**	n.s.	n.s.		0.0224
	KO	**	**	**	n.s.	n.s.	*	

Table 4: Pairwise comparisons of management strategies in terms of co-efficient of variation of mean net annual income.

Income	Strategy	CSR	PSD	PSF	ASR	MT1	MT2	KO
With no SR adjustment	CSR		0.9997	0.7951	0.0001	0.0001	0.0001	0.0007
	PSD	n.s		0.9477	0.0000	0.0000	0.0000	0.0002
	PSF	n.s	n.s		0.0000	0.0000	0.0000	0.0000
	ASR	**	**	**		1.0000	1.0000	0.9994
	MT1	**	**	**	n.s.		1.0000	0.9918
	MT2	**	**	**	n.s.	n.s.		0.9960
	KO	**	**	**	n.s.	n.s	n.s.	
With strategies at an equivalent SR	CSR		1.000	0.9536	0.0471	0.0208	0.1176	0.8978
	PSD	n.s		0.9909	0.0215	0.0088	0.0595	0.7671
	PSF	n.s	n.s		0.0020	0.0007	0.0069	0.3122
	ASR	*	*	**		1.0000	0.9998	0.5263
	MT1	*	**	**	n.s.		0.9951	0.3471
	MT2	n.s	n.s.	**	n.s.	n.s.		0.7585
	KO	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	
With strategies at their local optimum SR	CSR		1.0000	0.9443	1.0000	1.0000	0.8875	1.0000
	PSD	n.s.		0.9888	1.0000	0.9985	0.7449	1.0000
	PSF	n.s	n.s.		0.9622	0.8627	0.2773	0.9814
	ASR	n.s.	n.s.	n.s.		0.9999	0.8530	1.0000
	MT1	n.s.	n.s.	n.s..	n.s..		0.9579	0.9994
	MT2	n.s.	n.s.	n.s.	n.s.	n.s.		0.7891
	KO	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	

Table 5: Pairwise comparisons of management strategies in terms of mean annual mortality.

Income	Strategy	CSR	PSD	PSF	ASR	MT1	MT2	KO
With no SR adjustment	CSR		0.9127	0.9738	0.0000	0.0000	0.0000	0.0000
	PSD	n.s.		1.0000	0.0013	0.0002	0.0022	0.0001
	PSF	n.s.	n.s.		0.0005	0.0001	0.0009	0.0001
	ASR	**	**	**		0.9977	1.0000	0.9970
	MT1	**	**	**	n.s.		0.9916	1.0000
	MT2	**	**	**	n.s.	n.s.		0.9898
	KO	**	**	**	n.s.	n.s.	n.s.	
With strategies at an equivalent SR	CSR		0.9592	0.9888	0.4659	0.0486	0.6925	0.8693
	PSD	n.s.		1.0000	0.9618	0.3950	0.9963	1.0000
	PSF	n.s.	n.s.		0.9018	0.2731	0.9811	0.9987
	ASR	n.s.	n.s.	n.s.		0.9318	0.9999	0.9939
	MT1	*	n.s.	n.s.	n.s.		0.7858	0.5815
	MT2	n.s.	n.s.	n.s.	n.s.	n.s.		0.9999
	KO	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	
With strategies at their local optimum SR	CSR		0.9031	0.9705	0.9828	1.0000	0.9254	1.0000
	PSD	n.s.		1.0000	0.9998	0.8905	1.0000	0.7843
	PSF	n.s.	n.s.		1.0000	0.9647	1.0000	0.9050
	ASR	n.s.	n.s.	n.s.		0.9788	1.0000	0.9342
	MT1	n.s.	n.s.	n.s.	n.s.		0.9147	1.0000
	MT2	n.s.	n.s.	n.s.	n.s.	n.s.		0.8200
	KO	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	

Table 6: Pairwise comparisons of management strategies in terms of co-efficient of variation of mean annual mortality.

APPENDIX 3: SUMMARY OF MODEL VARIABLES

Variable	Description	Units
d	the digestibility of the diet	
PL_{diet}	the proportion of live material in the diet	
d_L	the digestibility of live material	
d_d	the digestibility of dead material	
PL_{sward}	the proportion of live material in the sward	
M	the actual mass of the individual	kg
n	indicates selectivity as an allometric function of mass	
c, d	parameters relating selectivity to grass type	
I	daily dry matter intake	kg
I_d	asymptote defined by the animal's digestive capacity	
B	vegetation biomass	$kg.ha^{-1}$
r	residual biomass below which animals cannot graze	$kg.ha^{-1}$
b	size-related constraint	
A	the mature mass of the animal	kg
u_g	factor scaling gut capacity to body mass	
b	allometric function of mass with a negative exponent	
p, q	vegetation-type specific parameters	
EI	daily energy intake	$MJ.day^{-1}$
I_B	the incisor arcade breadth	mm
a	a species-specific parameter accounting for size	
B_i	bite rate for process i (i = 1,2,3)	s^{-1}
V_{max}	maximum foraging velocity	$m.s^{-1}$
R_{max}	maximum eating rate	$kg.s^{-1}$
w	width of search park	m
D	bite density	m^{-2}
n	parameter governing time lost to future potential intake while stopping to take a bite	s
E_{exp}	net metabolisable energy expended	$MJ.day^{-1}$

Variable	Description	Units
FM	fasting metabolism	$MJ.day^{-1}$
E_{graze}	energy expended whilst grazing	$MJ.day^{-1}$
E_{mov}	energy expended by moving whilst grazing	$MJ.day^{-1}$
E_{com}	energy expended by commuting between grazing sites	$MJ.day^{-1}$
GT	grazing time	s
F_{dist}	distance moved while feeding	m
CT	time spent commuting	s
C_{dist}	distance travelled while commuting	m
COMVEL	velocity at which the animal commutes	$m.s^{-1}$