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Modelling the Influence of Rainfall Variability and Different Grazing Systems on the Spatiotemporal Dynamics and Productivity of Semiarid Rangelands

University of Cape Town

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DECLARATION

Thesis title: *Modelling the Influence of Rainfall Variability and Different Grazing Systems on the Spatiotemporal Dynamics and Productivity of Semi-Arid Rangelands*

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The study reported in this thesis forms part of the research project under the Rangeland Modelling Group in the Department of Mathematics and Applied Mathematics. Chapters 1- 2 and Chapters 4-6 are my own unaided work. Chapter 3 describes Richardson's (2000) savannah mechanistic model with a number of modifications to suit my study. The model was one of the initiatives of the Rangeland Modelling Group and Chapter 4 constitutes part of the model development process.

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ABSTRACT

In semi-arid/arid rangelands, an obstacle to sustainable livestock production arises from the complex interactions between variable rainfall and the effects of chronic intensive grazing. While many other factors affect sustainable grazing management, rainfall imposes limits in plant production, since growth period is usually short, yet the rainfall onset is unpredictable. The interaction between the effects of heavy stocking and belated rainfall, further curtail plant growth, making it challenging to effectively engage various grazing management strategies. Despite many decades of research, field trials testing the use of rotational grazing systems, as potential grazing management options, have largely yielded inconclusive results. This study pursued a two-fold objective: firstly, to broaden our knowledge about the rainfall-plant-animal system dynamics; and secondly, to re-examine the rotational grazing system with modelling as a substitute to field trials.

In this study, simulation results show that, when light stocking is adopted, the option for rotational grazing does not apply, as plant and animal responses are virtually the same as responses under continuous grazing management procedure. Otherwise, when rotational grazing is implemented, many factors must be considered and carefully synchronized in the scheme. These factors include: proper consideration for the onset of rainfall and grazing schedules, stocking rate vs. period of resting paddocks, and the number of paddocks in the rotational cycle vs. sizes of individual paddocks. The study further reveals that, when medium and high stocking rates are coupled with fewer paddocks and ample period of resting individual paddocks, rotational grazing yields both higher plant and animal productivity than continuous grazing management with similar stocking rates. The findings suggest that results of studies on rotational grazing systems depend on the spatiotemporal scales of evaluation besides pasture characteristics. Lastly, the study draws important implications for vulnerability of semi-arid rangelands to the impacts of climate change, and further suggests that farmers could effectively engage rotational grazing systems as adaptation measures.

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ACRONYMS

ADMI:	Average Daily Dry Matter Intake
ANPP:	Annual Net Primary Production
ARC:	Agricultural Research Council
C:	Carbon
CA:	Cellular Automata
CG:	Continuous Grazing
CO_2:	Carbon dioxide
CSG:	Controlled selective grazing
CSIRO:	Commonwealth Scientific and Industrial Research Organization
DR:	Deferred Rotation
DMI:	Dry Matter Intake
FAO:	Food and Agriculture Organisation
HILF:	High Intensity-low frequency
HPG:	High production grazing
HUG:	High utilization grazing
MtCO2e:	metric tons of CO_2 equivalent
RG:	Rotational Grazing
RR:	Rest Rotation
SD:	Short Duration
SDG:	short duration grazing
SRG:	Short rotational grazing
UNCCD:	United Nations Convention to Combat Desertification

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Chapter 1

General Introduction

1.1 Overview

While many decades of research have led to significant advances in our understanding about rainfall-plant–livestock interactions (e.g. Noy-Meir, 1973; Sinclair & Fryxell, 1985; Ellis & Swift, 1988; Westoby, et al., 1989; Behnke & Scoones, 1993), semiarid/arid rangelands remain inspirational for grazing studies and a testing ground for competing management strategies. The most dominant feature of semiarid rangelands is their low and highly variable rainfall, which makes it difficult to devise effective grazing management strategies to cope with yearly fluctuations in plant production. During dry years, forage becomes scarce and availability controls intake as animals have little choice. Range managers are required to adhere to light stocking rates in order to ensure that animals satisfy their immediate nutritional needs, and ultimately reduce the risks of financial losses due to mortality. Over and above, farmers aim at preventing the long-term effects of rangeland degradation.

However, in years of abundance, a large proportion of the forage decomposes since animals consume only a small fraction. As a management response, farmers might increase stocking rates with the intent to exploit emerging windows of abundant forage. Unfortunately, due to uncertainty of the production system, and driven by the perception that lower stocking and profitability are not compatible, farmers might almost invariably overstock the pasture in anticipation of superior economic returns (Walker, 1993). Consequently, due to grazing selection, the intensity and frequency of defoliation on patches reduce the quality and quantity of subsequent plant growth (Teague & Dowhower, 2003; Teague et al., 2004; Baumont et al., 2005). However, these effects of grazing and rainfall variability are management-dependent. Against this background, the thesis argues that our knowledge about the interactions between

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rainfall variability and defoliation effects must be generated at relevant spatiotemporal scales of grazing management units for effective prescriptions.

The rainfall-plant-livestock nexus represents only one dimension of the problem affecting management of semiarid rangelands. As livestock production systems vary from nomadic or semi nomadic to sedentary, and subsistence to commercial ranching systems; in many parts of the word, the legal frameworks, socio-economic and institutional issues are highly dynamic as is the case with the ecological system. This entails the need for comprehensive but integrated approaches to studying dynamics of rangelands. Evidently, a number of authors insist that environmental problems are the heart of human problems, for which scientific understanding may not be sufficient to bring out resolution (Ludwig et al., 1993; cf. Lee, 1993). This is indisputable nevertheless; the thesis presented here makes recommendations only on the rainfall-plant-livestock question, since it is supported by long-term existing data. Consequently, the study is limited as it deals with a scenario, which may only be applicable to commercial farming systems. Unlike communal and pastoral areas, the socioeconomic and institutional issues, which influence production, can be relatively controllable in ranching systems under private ownership. This assumption is reasonable since commercial systems are believed to be not susceptible to the consequences of what Hardin (1968) calls “tragedy of the commons” (cf. Bromely & Cernea, 1989). However, because of the uncertainty created by high rainfall variability, commercial systems could be subject to ratchet effect (cf Caddy & Gulland, 1983). By extension, the ratchet effect, which results from overexploitation of the natural resources in general, could arise in grazing management by the lack of inhibition on overstocking during good periods of rainfall, but strong pressure not to destock during bad years. Hence, like open access regimes, private property regimes such as ranching systems cannot be regarded as being completely protected from overexploitation, largely because of the uncertainty caused by large variability in rainfall.

In commercial ranching systems moreover, application of various management strategies to overcome the rainfall-plant-livestock bottleneck can be effectively frustrated on practical and economic reasons. For example, traditional extensive grazing management (continuous grazing) is a problem, primarily of stocking rate and season (Holechek et al., 1999, 2003; Barnes et al., 2008), besides being a recipe for selective grazing (Briske & Heitschmidt, 1991; Teague & Dowhower, 2003). While opportunistic strategies prescribed by Westoby et al. (1989) are intuitively appealing,

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they are not economically optimal (cf. Campbell et al., 2000; Higgins et al., 2007), and not always adequate to maintain the long-term productivity (Muller et al., 2007). Similarly, the question about whether rotational grazing systems are more effective than continuous grazing management procedure is highly contentious, yet dominating the grazing literature for decades (e.g. Heady, 1961; Denny & Barnes, 1977; Savory, 1983; Barnes et al., 2008; Muller et al., 2007; Briske et al., 2008; Mashiri et al., 2008; Teague et al., 2008b). Despite that, ongoing research holds promise to give livestock producers and land mangers improved rotational grazing systems to enhance sustainability of grazing on semiarid rangelands (e.g. Kirkman & Moore, 1995; Teague & Downhower, 2003; Barnes et al., 2008; Mashiri et al., 2008). For example, rotating high stocking biomass can overcome bush encroachment as it is believed to enhance uniform defoliation across plant species, thereby decreasing the competitive advantage of less preferred species (Kirkman & Moore, 1995; Teague & Downhower, 2003). Moreover, studies suggest that, rotational resting and rotational grazing are tools to decrease grazing impacts with considerable potential to enhance both livestock production and resource condition. However, rotational grazing systems urgently needed further re-examination (Norton, 2003; Teague et al., 2009); hence, the motivation for this study.

1.2 Why Study Rangelands?

Besides the obstacle articulated above, there are many compelling reasons to study rangelands. Importantly, the maintenance or restoration of rangeland health and resilience is a critical social imperative, which requires sound knowledge in order to ensure future supply of their goods and services (e.g. Teague et al., 2008a; Teague et al., 2009). Certainly, rangelands are beneficial in various ways, and livestock production represents the main historical use (Chang & Xia 1994; Snyman, 1998). Foremost, the history of civilization has seen giant strides since ancestors began to domesticate and herd grazing animals. Production of livestock from natural forage supported the ancient Mesopotamian, Egyptian, Greek and Roman civilizations**.** Progressively, rangelands form the primary land use type in the world (FAO, 2000; Holechek et al., 2001). They are used to produce nearly 25 percent of the global meat (Halweil, 1998), and support at least one billion people all over the world who use them for their livelihoods (UNCCD, 2004). In developing countries, there are at least 40 million pastoralists who depend on natural grazing for their livelihoods; most are

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subsistence herders. In sub-Saharan Africa, semi-arid rangelands constitute 55 percent of the subcontinent's area with 57 percent of the biomass of domestic ruminants (Sandford, 1995; Richardson, 2004). These regions sustain an intimate relationship between household socio-economic conditions and rangeland productivity, of which the decline negatively affects family income, health and the distribution of scarce resources (World Bank, 1991).

Ecologically, rangelands provide services such as stable soils, reliable and clean supplies of water, and the natural occurrence of plants, animals and other organisms essential for aesthetic and cultural values (Grice & Hodgkinson, 2002; Teague, et al., 2008a). With global concern over climate change, rangelands have the potential to sequester carbon, and therefore a promising opportunity for mitigation of climate change. Smith et al. (2007) estimate that improved rangeland management has a biophysical potential to sequester 1300-2000 MtCO2e, depending on rangeland types. Rangeland-based adaptation strategies – such as seasonal grassland reserves (Angassa & Oba, 2007) or revival of traditional grazing systems and development of forage reserves (Batima, 2006) – are likely to improve productivity and soil carbon sequestration, and play roles in both adapting to and mitigating further climate change (Tennigkeit & Wilkes, 2008). Similarly, stocking rate management, rotational, planned, or adaptive grazing, and enclosure of grassland from livestock grazing might further increase C sequestration.

However, from a management viewpoint, the net reactions of grazing land to environmental crises are difficult to predict, because of the complexity of the ecosystem and its many interacting links. Some rangelands are sensitive to environmental changes, while others appear quite resilient (Skarpe, 1991). This makes the assessment of rangeland responses to various grazing management strategies a complex subject. The thesis addresses two essential themes. The first theme relates to understanding how the rangeland system works with regard to rainfall-plant-animal interactions, but these are analyzed in the context of evaluation of grazing systems - as the second theme. In the interest of clarity, the objectives of these themes have been described separately, although they are not treated mutually exclusive.

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1.3 Key Themes

Since production of livestock was one of the factors which gave birth to the ancient civilizations, conceivably overgrazing of the range could be one of the causes of their decline, and therefore the need for effective management. Today, expansion of bush encroachment in semi-arid savannahs throughout the world is a form of degradation widely attributed to the effects of overgrazing (Skarpe, 1991; Sidahmed & Yazman, 1994; Jeltsch, Weber & Grimm, 2000; Tobler, Cochard, & Edwards, 2003). Arid and semi-arid areas are ecologically sensitive, yet they are severely subjected to grazing pressure (Snyman & Fouche, 1991; Holm et al., 2003), causing their rapid degradation (Snyman & Fouche, 1993; O’Connor & Roux, 1995; Flemmer et al., 2003). However, shrub invasion is multifaceted. Besides overgrazing many factors are involved, making it difficult to separate their effects (Humphrey, 1987). Recently, bush encroachment is linked to increasing global levels of atmospheric CO_2 (Polley et al., 1994; Bond et al., 2003; Tietjen & Jeltsch, 2007). Furthermore, the effects of variable rainfall superimposed on a background of overgrazing are believed to initiate a chain of events, resulting in serious impairment of rangeland productivity but lasting many years (Dye, 1984). The selective use of plants and landscape components by livestock can cause a gradually widening area of degradation under continuous grazing, even at light to moderate stocking rates (Ash & Stafford-Smith, 1996; Teague et al., 2008b).

Consequently, rangelands which appear sensitive to degradation suffer great losses in vegetative cover, accelerated soil erosion, loss of soil fertility and structure, and a reduction in biodiversity (Skarpe, 1991; FAO, 2000). Albeit, Richardson (2004) subscribes to the effect that expected long-term decline in livestock numbers in communal areas as a result of overgrazing has not been observed in southern Zimbabwe (Scoones, 1993), in the Herschel District of the Eastern Cape (Vetter et al., 1998) or Namaqualand (Hoffman et al., 1999). Other workers equally dispute the suggestion that domestic livestock, even with heavy stocking rates, inevitably cause rangeland degradation and a decline in productivity (Behnke & Scoones, 1993; Tapson, 1990). Elsewhere, long-term heavy grazing did not reduce cattle performance (Fynn & O’Connor, 2000). Perhaps the bipolar conception about rangeland degradation reflects the notion that some are resilient while others are fragile (Holling et al., 1995), especially when subjected to grazing impacts.

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Although the causes of shrub invasion and other forms of rangeland degradation are variable and often contested, their economic consequences are generally of great concern to range managers, national and international policy makers. According to the 1991 United Nation assessment, annual production losses from rangeland degradation accounts for US$23 billion globally, $7 billion of which result in Africa (Earth Policy Institute, 2002). Walker (1993) argues that some rangelands have been degraded due to lack of understanding of how rangelands work. This has resulted in failure of planners and mangers to correctly relate cause and effect. Therefore, the whole story conveys the need for effective planning and management which more importantly requires that the behaviour of the system be understood (Richardson et al., 2007).

In view of the foregoing arguments, one theme of this study deals with understanding the dynamics of rangelands as influenced by the interaction between rainfall and grazing livestock. The second theme addresses one of the most intensively studied areas in grazing management – the rotational grazing systems. However, grazing systems and related questions are difficult to address with field trials in a thorough manner because of the need to consider various spatial and temporal scales involved in order to capture variable responses meaningfully. This study approached the problem with modelling and was preferred to field experiments because of its flexibility in dealing with complex systems. Modelling holds the predictive power to extend field results and presumably circumvent potential problems inherent in field trials. For example, modelling facilitates integration of individual processes and their interactions within a rangeland system (Biot, 1993; Thornely, 1998), thereby enabling analyses, and comparison of various scenarios, and ranking them according to their effects. Realizing this opportunity, an existing savannah model of Richardson (2000) was adapted and used to simulate the system to appraise rotational against a continuous grazing management procedure..

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1.4 Context of the Study

The study was undertaken as an integral part of a research program which has had a series of research activities (Richardson, 1994; Richardson et al., 2000; Hahn et al., 2005; Richardson, Hahn & Hoffman, 2005; Richardson, Hahn & Hoffman, 2007; Richardson, Hahn & Hoffman, 2007a; Richardson, Hahn & Hoffman, 2007b). Aimed at understanding the factors affecting productivity and sustainability of arid and semi-arid pastoral systems in the region of Southern Africa, previous works of the program have *inter alia*, focused on evaluation of grazing strategies on animal production (Richardson et al., 1991), long-term climate, livestock and vegetation interactions and sustainability (Richardson et al., 2001a, b, c). The current study is a contribution to these efforts, specifically, by adapting "a model of a livestock production system for a Southern African savanna; VELDSTOCK developed by Richardson (2000). The current work extended the model to a multi-paddock system; programming it in *Matlab* computer language and evaluating its performance and using it to address the research problem under consideration.

1.5 The Research Gaps

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A fundamental ecological dilemma in grazing management emerges on how to simultaneously optimize the interception and conversion of solar energy into primary production and the efficient harvest of the primary production by herbivores (Parsons et al., 1983). Climatically induced variations and the widespread occurrence of selective grazing, in response to variability (O'Reagain & Schwartz, 1995) both complicate the managerial tasks involved in optimizing primary production (Briske & Heitschmidt, 1991). The scientific community is aware of the importance of exploiting the spatial and temporal variability within grazing lands as a key factor for sustainable use (e.g. Coughenour, 1991; FAO, 2000; Norton, 2003). Range managers have attempted manipulation of range components to obtain sustainable and optimum combination of goods and services (Holechek et al., 2001). Unfortunately, spatial management has been based on tradition, trial and error, subjective judgements or poorly designed conceptual models (Coughenour, 1991; Norton, 2003).

Moreover, the grazing literature documents that, our understanding about plant responses to defoliation, animal selectivity across spatial and temporal scales, and grazing impacts on ecosystem landscapes and plant communities remains in need of testing and refinement (Coughenour, 1991; Norton, 2003; Teague & Downhower, 2003). Comprehensive understanding of the influences of variable rainfall coupled with the foraging behaviour of livestock will help design effective management procedures to ensure the long-term productivity of rangelands. In semi-arid/systems the assessment of grazing procedures, seasonal and spatial patterns of forage supply, and often high inter-year variability must be accounted for. The study pursued two general objectives justified as follows:

1.5.1 Objective 1: Increase Our Understanding about How the System Works

Knowledge of ecological processes can help managers be more effective in implementing strategies that enhance positive responses, reduce or mitigate negative responses, and benefit the financial efficiency and human relationships of a ranch business (Teague et al., 2008b). This knowledge can be effective if directed towards the system dynamics at the proper spatiotemporal scales of grazing management units for timely decisions and rapid risk management of the grazing enterprise. Along this reasoning, the first general objective of the study sought to further explore the influence of seasonally variable rainfall, intensity, timing and period of grazing on the dynamics of a semi-arid savannah rangeland. This objective stems from realization that, the past two decades has seen much progress in our understanding about the influence of climate-plant-livestock interactions in semi-arid rangeland. A huge literature is in near total agreement of the non-equilibrium behaviour of arid/semi-arid rangelands, whereby the system dynamics is driven by rainfall (DeAngelis & Waterhouse, 1987; Ellis & Swift, 1988; Fernández-Giménez, & Allen-Diaz, 1999). Plant growth and distribution are regulated by precipitation and tend to be highly variable: intra annually (Rutherford, 1978; Solbrig, 1993); inter annually (Thyson, 1986; Ellis & Swift, 1988; Ellis, 1994); and spatially (Ellis & Swift, 1988, Coughenour, 1991; Bayer & Waters-Bayer, 2004; Sala et al., 1988; Scholes & Walker, 1993). Consequently, livestock populations fluctuate widely over time due to changes in reproductive and survival rates (Hoffman et al., 1999).

However, progress in understanding the influence of rainfall variability at the most appropriate spatiotemporal scale of grazing management units is generally limited. Our knowledge about the system has been immensely devoted at large landscapes over long time scales (e.g. McNaughton, 1985; Sala et al., 1988). Understanding within year, seasonal variations of annual net primary production (ANPP) is at the core of many issues in ecosystem ecology and animal production in natural grasslands (e.g. Vallentine, 2001). Yet, whole year inter-annual variations of ANPP have received much more attention than seasonal variations and more than the interaction between seasonal and inter-annual (cf. Posse et al., 2005). Hence, the need for more work at the most relevant spatial scale of plant, paddock and whole farm matching with the time scale of

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days, weeks or months within a season. Activities of range managers most often operate within these spatiotemporal scales.

While knowledge of the role of rainfall in rangeland dynamics is comprehensive, our understanding about the influence of grazing is less so, and remains challenging. The "grazing optimization" hypothesis suggests that an optimal grazing intensity can increase primary production over that of an ungrazed system (McNaughton, 1979). However, Belsky (1986) contends that this does not appear to be a dominant ecological process operating on a regular basis in rangelands. The hypothesis is thought to exaggerate the potential increase in primary production resulting from an optimal level of grazing relative to the potential decrease, which might occur in response to severe grazing (Briske & Heitschmidt, 1991). In reality, severe grazing ensures that available production is efficiently harvested, but eventually reduces production by minimizing the subsequent capture of solar energy **(**Briske & Heitschmidt, 1991). Grazing removes leaf area that is necessary to absorb photo-synthetically active radiation which converts it into chemical energy (Briske & Richards, 1995). The reduction in photosynthesis negatively affects root systems by reducing energy available to support existing root biomass and retarding new root production.

Conversely, lenient grazing maximizes primary production, but a large percentage of the production decomposes without being consumed by herbivores; hence compromising efficiency in forage harvest. Moreover, grazing does not occur uniformly over time or over a landscape (Bailey et al., 1996). Livestock grazing large paddocks exhibit spatial patterns of repetitive use, heavily using preferred patches and avoiding or lightly using others (Teague et al., 2004). Teague and colleagues argue that patch-selective grazing translates into higher stocking rate on heavily used patches than that intended for the area as a whole, and periods of below average precipitation compound the effects of herbivory, providing periods of accelerated deterioration. Now, considering the important role of rainfall in semi-arid/arid areas the motivation would be to understand the interactions with grazing and explore how they impede the performance of rotational grazing management procedures.

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1.5.2 Objective 2: Re-Examine Rotational Grazing Systems with Modelling

Understanding effectiveness of various grazing management strategies and choosing them according to their performance can allow for efficient allocation of limited resources to achieve both immediate and long-term goals of the grazing enterprise. The use of rotational grazing systems has a powerful basis on the understanding that the root cause of rangeland degradation is overgrazing and/or management failure. Hence, the second general objective of the study was to re-examine grazing systems as possible management options. The rationale is that, research in this area has largely followed field experimentation, and therefore the need to re-examine them with simulations as the alternative approach.

In this study, a grazing system is defined as "a specialization of grazing management which defines recurring periods of grazing and deferment for two or more pastures or management units" (Briske & Heitschmidt, 1991). Decisively, rotational grazing systems are implemented consistent with the behaviour of migratory herbivores on the presumption that many natural ecosystems have a high inherent sustainability (Frank & McNaughton, 1993), despite that they support more herbivore biomass, and sustain considerable higher levels of herbivory than any other terrestrial habitat (McNaughton et al., 1989). One probable hypothesis postulates that migrants make more efficient use of resources than residents do (Fryxell et al., 1988). Periodic movements allow migrants shift to fresh pastures when their own grazing has depleted the supply of food. This in turn allows vegetation a period free from grazing during which aboveground tissues restore. Since growth is often highest at intermediate levels of vegetation abundance (Noy-Meir, 1975), seasonal migration could increase grassland productivity, and therefore allow more population of consumers (Fryxell et al., 1988). Nomadic pastoral systems that mimic these grazing patterns also seem to have less detrimental effects on vegetation (Danckwerts et al., 1993).

Simple emulation of the behaviour of migratory ungulates involves a number of tasks in the design and implementation of rotational grazing systems (Batabyal, 2001a). First, the manager divides the pertinent parcel of rangeland or cell into a number of fenced paddocks. Next, a herd of animals is brought into a particular paddock to graze for a specific period of time. Upon the completion of this time period, the animals are moved to the next paddock and the manager continues this process in a sequential manner. Following this principle, rotational grazing systems envisage to offer a number

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of potential benefits if used appropriately. These include maintaining or enhancing plant condition, increasing carrying capacity and therefore achieving high livestock production. Moreover, the objective of rotational grazing systems is to increase homogeneity of use in pastures by manipulating distribution and stocking rates in space and time (Teague et al., 2004; Derner & Hart, 2007; Hart, 1978; Fuhlendorf & Engle, 2001), and achieve fuller utilization (Coughenour, 1991). In spite of the seemingly logical principle, the use of rotational grazing procedures has been called into question (e.g. Heady, 1961; Briske et al., 2008). Strikingly, there is a bulk of literature advocating these systems as means of spatial management of grazing to enhance livestock production and resource condition (Norton, 1998; Teague & Downhower, 2003; Teague et al., 2004). Thus, the effectiveness of rotational grazing systems is less certain, and hence it has become persuasive to test their seductive theory against practical experience.

So far, this part of the literature review has identified a number of research areas to make a different contribution to this debate. First, studies on modelling rotational grazing systems are scanty. Due to increasing complexity in execution of field trials, possible limitations were postulated. Results from grazing system studies are contingent on the right combination of many variables of interest (cf. McMeekan & Walshe, 1963; Woodward et al., 1995); specifically determination of optimal rest periods for individual paddocks is germane (Morley, 1968; Parsons et al., 1988). Second, many grazing studies focus on measures of animal and above-ground plant responses. Roots and nonstructural components like carbohydrate reserves have been overlooked. It was envisaged that by incorporating these components in the analyses, new insights would emerge. Lastly, with the exception of few studies (Batabyal, 2001a; Barnes et al., 2008), there has been little consideration on the possible influence of the spatial component of grazing assessment, for instance the effects of varying number and size of paddocks in the rotational cycle (Norton, 2003). Grazing systems such as deferred rotation, high intensity-low frequency grazing, rest rotation, all have spatial and temporal control aspects to them (Holechek et al., 2001), and therefore ignoring them would affect the outcome of rotational grazing studies. Yet, many grazing studies and various reviews have concluded that multi-paddock grazing offers no significant benefit over continuous grazing (Holechek et al. 1999, 2000; Briske et al., 2008). A fresh look at the studies shows that they are largely small-scale trials focused on the technical questions of ecological impacts and livestock production conducted in a relatively

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limited scope of fairly resilient landscapes (Teague et al. 2008b). Clearly, these are critical gaps of some concern to the issue of understanding rangeland dynamics, application of grazing management prescriptions and assessment of their effectiveness.

1.6 Key Research Hypotheses

1. The effects of defoliation under continuous grazing management will depend on the intensity and frequency of grazing a pasture, irrespective of a grazing management strategy. At lower stocking rate plant and animal productivity will be similar between rotational and continuous grazing systems. However, at high stocking rates plant and animal production will be higher under rotational grazing than under continuous grazing system with similar stocking rates.

2. As the number of paddocks in a rotational cycle increases, grazing pressure in individual paddocks would also increase, depending on stocking levels, but the negative effects of defoliation would be reduced as the period of stay in individual paddocks gets shorter, especially during the critical periods of plant growth.

3. The benefits of grazing systems in terms of plant growth would diminish as rainfall decreases, but animal performance would be appreciable as efficiency in harvest would increase with increase in number of paddocks.

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1.7 Emerging Questions

The questions below served as a guide to a detailed literature review presented in Chapter 2.

1. What factors influence outcomes of studies comparing the performance between rotational and continuous grazing systems?

2. Which research issues in field trials have received little attention but could be considered with a modelling approach to address possible discrepancies?

3. Based on the knowledge about the interaction between variable rainfall and grazing, at the scale of grazing management units, what practical improvements to the design of rotational grazing systems are necessary?

1.8 Specific Objectives

The objectives presented below describe specific tasks undertaken to accomplish this study and the corresponding chapters are key study outputs. The objectives were to:

1. Review studies on grazing systems to address the preceding research questions in order to generate researchable questions.

2. Adapt existing model (s) [Richardson, 2000] such that the model simulates rainfall and soil moisture dynamics linking with plant growth and animal feedbacks in a multi-paddock pasture under a rotational grazing system.

3. Test and evaluate the model by verification, calibration, sensitivity analysis and where possible validate by comparison with empirical data.

4. Use the model to evaluate grazing systems and suggest practical modifications necessary to reap their purported benefits in grazing management.

1.9 Summary and Text Structure

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One of the challenges to sustainable management of semi-arid and arid rangelands is a consequence of the complex interaction between variable rainfall and chronic intensive grazing by herbivores. In commercial systems, many management solutions to the problem are limited by economic and practical considerations. In order to contribute prescriptions in sound management, the chapter proposed the need to increase our understanding about how the system works, especially at the smaller scales of grazing management units. Investigations testing the use of grazing systems as potential management options have largely followed field trials, but yielding inconclusive results. The use of modelling, despite its predictive power to extend field trials has lagged behind empirical investigations. The chapter proposed using simulations to re-evaluate rotational grazing systems and make more contribution to the ongoing debate in this field. The rest of the text is organized into five more subsequent chapters, with each chapter addressing one of the activity objectives described in Section 1.8.

Chapter 2: This chapter is logically an extension of Chapter 1. The objective is to examine grazing studies through literature review and address questions posed under Section 1.5. The chapter identifies critical issues, which influence outcomes of grazing studies and thus, the need for serious considerations in their execution. Experimental designs and use of statistics, and the design and implementation of rotational grazing systems are discussed to illuminate why field trials of rotational grazing yield results which may contradict experiences and/or expectations of farmers who continue practicing grazing systems. Chapter 2 further revisits theories and methodological approaches to modelling rangeland dynamics. The equilibrium and non-equilibrium theories are particularly discussed to show the conceptual relevance of the study to the current state of knowledge in rangeland ecology. Modelling approaches are reviewed to identify model(s) most suitable for the study.

Chapter 3: The objective of this chapter is to describe the structure and provide mathematical statement of adapted version of the Savannah Model. Three interlinked modules of soil water balance, plant growth, and diet selection and food intake are presented. The most important feature of the soil-water balance module relates to its influence on plant growth varying according to diurnal and seasonal rainfall. Variation in plant biomass responds to soil moisture dynamics. The diet selection and food intake module describes diet composition, its linkage to availability and the animal weight as a response variable.

Chapter 4: Chapter 4 introduces evaluation process of the model and presents detailed tests of its behavioural responses to changes in rainfall, stocking rates, initial values of response variables, and changes to standard parameter values. The major purpose of Chapter 4 is to refine and reduce possible inconsistencies in the model structure and components. A sensitivity analysis identifies parameters in need of further research to determine their accurate values.

Chapter 5: This chapter primarily deals with a detailed diagnosis of the rotational and continuous grazing procedures for evaluation. The primary tests involve understanding how plant growth responds to grazing systems at comparative stocking rates. Similarly, plant responses to changes in the number of paddocks in the rotational cycle are explored. Subsequent experiments present analyses of animal responses to rotational and continuous grazing. Results generally indicate that plant responses to a grazing system are relatively complicated to interpret. It all depends on the combination of number of paddocks and stocking rates, timing and period of grazing, and pasture

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characteristics. The spatiotemporal scale of measurement is one the most crucial factors when judging the performance of a grazing system. Overall, the interpretation of animal responses was clear-cut, and generally in favor of rotational grazing.

Chapter 6: The last chapter provides a general discussion and draws broad conclusions of the research. The chapter further discusses policy and management implications of the findings. The chapter addresses the ultimate research question: *Based on the knowledge about the interaction between variable rainfall and grazing, at the scale of grazing management units, what practical improvements to the design of rotational grazing systems are necessary?* Lastly, the chapter suggests future research topics.

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Chapter 2

Grazing Studies, Theories and Approaches to Modelling Rangeland Dynamics:

A Review

2.1 Introduction

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The development of rotational grazing systems has evolved alongside serious expression of doubts about their benefits. Considerable amount of research has been accomplished, and reviewers have carefully examined a large collection of field experimentation (e.g. Heady, 1961; Gammon, 1978; Pieper, 1980; Heitschmidt & Taylor, 1991; Holechek et al., 2000; Vallentine, 2001; Briske et al., 2008). Emerging conclusions are widely at variance when matched against reports from ranchers, graziers, and pastoralists in North America, southern Africa, and Australia who claim that rotational grazing has caused improvement in species composition and productivity of their land while maintaining or even increasing stocking rate (cf. Norton, 2003). Clearly, two different standpoints regarding the value of grazing systems in rangeland management persist. Unfortunately, scientists are unable to experimentally, duplicate the success stories of the practical farmer. Hence, the evidence in favour of intensive rotational grazing from farmers is overall anecdotal, and the opposing perspective emerges from research literature and textbooks (Barnes et al., 2008). However, there is also a bulk of literature advocating the use of grazing systems in rangelands (Booysen, 1975; Booysen & Tainton, 1978; Kirkman & Moore, 1995; Teague et al., 2004; Norton, 1998; Teague et al., 2009).

The current study is modelling-based. Like any other approaches, field trials have potential flaws and part of this review identifies and discusses them and shows how they are capable of influencing outcomes of grazing studies. The review revisits two contrasting paradigms deliberated in the recent literature of equilibrium and non-equilibrium theories. Thus, the chapter comprises three broad aspects of the literature:

studies on grazing systems, theoretical advances in ecology, models, and modelling approaches. Eventually, the chapter makes a humble contribution to the study of grazing systems in two different ways. Firstly, it takes a step further from previous works to explain why many findings of rotational grazing systems contradict field experiences and identifies very specific topics for studies to consider. Secondly, the chapter improves on a conceptual scope against which managers can re-evaluate their own management procedures and identify areas for refinement.

2.2 Review Methodologies

2.2.1 Existing Techniques and Gaps

The field of ecology handles reviews in three main different ways: (1) as a large pool from which a small number of exemplars are selected to illustrate particular ecological principles or argument; (2) as a source for narrative qualitative reviews, as well as the discussions of most primary research papers; or (3) as a database from which to conduct semi-quantitative reviews using vote-counting procedures (cf. Osenberg, Sarnelle, & Goldberg, 1999a). In studies of grazing systems, Norton (2003) applied the first approach to critique rotational grazing studies and argued for the need to pay more attention to the spatial aspects of grazing management. The larger part of the most recent review on grazing systems exercised the third approach to direct the profession toward a reconciliation of perceptions in support of rotational grazing systems with that of the experimental evidence (Briske et al., 2008). Innovative approaches such as meta-analysis have been applicable in resolving inconclusive findings from studies addressing a particular issue of this kind. It is a quantitative synthesis, analysis, and summary of a collection of studies (Hedges & Olkin, 1985; Stanley, 1998). The technique has been used in entomology to review conflicting evidence on the role of ants as plant biotic defences (Rosumek et al., 2009). However, synthesis studies in the grazing literature which have applied this technique are not available. Certainly, objectives of the literature review dictate the choice of methodologies to undertake.

The methodology employed in this study seeks to generate research questions. It adopts a two-pronged approach involving narration and a discussion of selected studies to reanalyse studies on grazing systems. The choice of this approach recognises that the recent review by Briske et al. (2008) has exhaustively summarised the state of knowledge about rotational and continuous grazing systems. Application meta-analysis

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technique is beyond the scope of this study although it could have been useful to attempt to resolve possible conflicting findings on rotational and continuous grazing studies. The central argument is therefore to show that the findings on studies of rotational grazing largely remain inconclusive and, thus premature to repudiate them.

2.2.2 Review Processes

It is tempting for authors of narrative reviews to consciously or unconsciously select and describe studies to support their own understanding of the literature and/or their own established theoretical predispositions. Important steps were taken to avoid this situation. The starting point was to access and thoroughly scrutinize the most current syntheses on grazing systems (e.g. Norton, 2003; Briske et al., 2008). The initial choice of the two studies was based on their divergent inferences on the subject matter. These reviews indicate primary field studies and previous reviews (e.g. Heady, 1961). Where possible referred studies were searched to confirm and extract information deemed necessary. However, to keep with relevance the search paid more attention to studies pertinent to semiarid/arid areas – the primary focus of the study.

The second step, involved continuous consultations with research workers such as David Richardson[1] and Richard Teague[2]. Through consultations and literature review, the background to the research problem was refined. Subsequent steps involved listing all the studies accessed, identifying conflicting findings, and at times tried to group or otherwise configure those that had various types of results or outcomes. This approach ensured that either any interesting finding from a single or group of studies be fully considered and methodically discussed. The obstacle however, was to find as many recent empirical studies as relevant to the study sites of southern Africa. The subsequent section presents the major findings of the review. The presentation follows the objectives of the study outlined in Chapter 1, but not necessarily in the order presented in Chapter 1.

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[2] Richard Teague is Associate Professor at Texas AgriLife Research

2.3 A Review of Grazing Systems

One part of the general objective of this study proposed to re-examine grazing systems focusing on the spatiotemporal scale of grazing management units (Chapter 1, Subsection 1.4.2). This section forms part of the review that provides an account of the concept of grazing systems, advances in studies of grazing systems and identifies critical research gaps. The review is guided by the first two questions presented in Chapter 1 such as:

1. What are the possible factors influencing various outcomes of studies comparing the performance between rotational and continuous grazing systems?
2. Which of the factors have received little attention and could be considered with a modelling approach and possibly overcome possible problems associated with field trials?

2.3.1 Concepts and Definitions

The term *grazing system* is often used in the range literature in two different ways. In one case, it is used to denote a grazing strategy, meaning "a specialization of grazing management which defines recurring periods of grazing and rest for two or more pastures or management units" (Soc. Range Manage., 1983; Heitschmidt & Taylor, 1991). In Noy-Meir’s (1975) analyses of stability concepts, the term has been used to denote a given animal with vegetation, construing somewhat an ecosystem with a grazer and the vegetation as major components. Sometimes the term grazing system can be used to mean production systems such as commercial and subsistence livestock production. The meaning of grazing system in this thesis widely refers to the first concept.

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2.3.2 Intellectual Origin of Grazing Systems

The origin of grazing system concept is documented in three separate papers (Heady, 1961; Coughenour, 1991; Briske et al., 2008). According to Coughenour (1991), the concept dates back to the end of 19th century initially advocated by Jared Smith in the U.S.A. Other documentations suggest that at the near end of the 18th century, James Anderson described grazing systems in Scotland (Voisin, 1959; e.g. Briske et al., 2008), but its implementation is a relatively recent phenomenon. Originally, Smith (1896) observed severe livestock overgrazing in the USA from 1885 to 1899, which prompted the proposal for "partial resting", involving alternating grazing among smaller subdivided pastures. Similarly, in South Africa, changes of the range from grassveld to dwarf shrub and bare soil were thought to be a result of continuous grazing (Howell, 1978; Coughenour, 1991). Consequently, the primary objective of grazing systems was to reduce the impacts of overstocking, but later on grazing systems were promoted to increase animal production by enhancing production of palatable species (Coughenour, 1991). Briske et al. (2008) have also described additional objectives of grazing systems including: a) reducing animal selectivity by increasing stock biomass b) ensuring more uniform animal distribution within large heterogeneous landscape and c) improving species composition or productivity by ensuring that the most preferred species have a rest period during the growing season. In line with these objectives, four kinds of management systems are categorized from van de Pol & Jordaan (2008), and summarized (Table 2.1). Grazing systems are evaluated on their ability to sustain production without causing adverse environmental effects, such as bush encroachment (Norton, 2003).

TABLE 2.1: A Typology of Grazing Systems, Characteristics and Corresponding Objectives

Grazing System	**Objective**	**Characteristic**
High production grazing (HPG)	Light utilization of palatable species for better animal production and plant condition	a minimum of four camps per herd, relatively short rotational cycle
Controlled selective grazing (CSG)	To ensure moderate utilization of palatable species to stimulate them and suppress unpalatable species	Eight or more camps required. Short periods of stay and long period of absence
High utilization grazing (HUG)	Total utilization of available forage to maintain veld condition and better animal production**	a camp is grazed until all grasses and including less palatable species are fully utilized
Short rotational grazing (SRG)	To ensure that palatable species are utilized only once during the grazing period. To prevent the second bite believed to be destructive.	8 camps or more are required. The period of stay is relatively short

**Production per animal is probably reduced by this method although production/ha may increase

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A different typology identifies the HPG and HUG as management tactics while Deferred Rotation (DR); Rest Rotation (RR); High Intensity-low frequency (HILF); and Short Duration (SD) are the major types of grazing systems (van de Pol & Jordaan, 2008). RR systems are either multi-pasture, multi-herd or multi-pasture, single herd. They are designed to maintain or improve range condition by utilizing a combination of HPG and HUG tactics. Notably, two features are common to all the four types of grazing systems. Firstly, all operate under temporal control by deciding the time period of rest (absence of grazing) and period of stay (period of grazing) for a single paddock. This is important to influence frequency of defoliation. Consequently, control over defoliation frequency, instead of continuous exposure to defoliation, is the essence of experimental hypotheses testing grazing systems (Norton, 2003). Secondly, all grazing systems are spatially controlled by establishing how much pasture area or number of camps for the grazing system of choice.

2.3.3 Progress in Grazing Research

Studies on grazing systems cover a long history of approximately six decades largely carried out in North America, Southern Africa, and Australia. By the mid of 20th century huge amount of information was collected prompting one of the most comprehensive reviews on the value of rotational and continuous grazing practices (Heady, 1961). Prior to Heady's (1961) review, Sampson (1951) briefly evaluated experimental studies (Briske et al., 2008). Recently, a critique has been presented (Norton, 2003), and field studies are being resumed (Teague et al., 2004; Derner & Hart, 2007; Barnes et al., 2008; Mashiri et al., 2008); a synthesis papers have been published (Briske et al., 2008; Teague et al., 2008b), and lastly projects with modified grazing systems have been described (e.g. van de Pol & Jordaan, 2008). The proposal for the redesigning of grazing systems suggests that more work is needed to provide policy direction on implementation of grazing systems. However, Briske et al., (2008) contends that further costly grazing experiments adhering to conventional research protocols will yield little additional information. Notwithstanding, a fresh scrutiny of the range of studies revisited in most reviews suggests a paucity of modelling studies especially in semi-arid rangelands of southern Africa, although a handful exist (e.g. Noy-Meir, 1976; Muller et al., 2007). Hence, the current study.

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2.3.4 Key Findings of Studies on Grazing Systems

This section provides a synopsis of major findings of studies comparing continuous and rotational grazing systems. A summary of key conclusion of major reviews in this field is presented based on the recent review by Briske et al. (2008). Contrasting point of views from Norton’s (2003) critique on grazing systems are also discussed (Table 2.2).

TABLE 2.2: Conclusions from major reviews of grazing systems research spanning the last 50 years of the rangeland profession. Experimental data have consistently indicated that rotational grazing is not superior to continuous grazing on rangelands (adapted from Briske et al. (2008).

Sampson (1951, p. 21)	‘‘two distinct viewpoints [exist] among range conservationists and operators regarding the merits of rotation or deferred-rotation grazing.’’
Heady (1961, p. 191)	‘‘specialized grazing system has no advantage in livestock production over continuous grazing, at least with good or excellent ranges under comparable stocking rates and degree of care in other management practices; … other management factors are more important in the production of livestock than system of grazing.’’
Van Poollen & Lacey (1979, p. 253)	‘‘land managers should place more emphasis on proper stocking intensity, and less on grazing system implementation.’’
O’Reagain & Turner (1992, p. 43)	‘‘Stocking rate is a major determinant of both range condition and animal production, and is possibly the most important management variable under the direct control of the grazer. Relative to this variable, the grazing system employed is of minor importance, with there being little apparent difference between continuous and rotational grazing systems.’’
Norton (2003)	“Primary producers claim that some forms of rotational grazing systems allow a substantial increase in stocking rates above previously recommended levels (an increase of at least 50 or 100% is common) without significant loss of individual animal production, with a concurrent improvement in rangeland condition and much higher profit margins”.
Briske et al. (2008)	“Continued advocacy for rotational grazing as a superior strategy of grazing on rangelands is founded on perception and anecdotal interpretations, rather than an objective assessment of the vast experimental evidence”.
	“The experimental evidence indicates that rotational grazing is a viable grazing strategy on rangelands, but the perception that it is superior to continuous grazing is not supported by the vast majority of experimental investigations. There is no consistent or overwhelming evidence demonstrating that rotational grazing simulates ecological processes to enhance plant and animal production compared to that of continuous grazing on rangelands.”

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Most if not all reviews of studies on systems agree that empirical evidence does not favour rotational grazing systems over continuous grazing, and this is despite claims about field experiences by the farmers (Table 2.2). Rather, most experimental studies conclude that stocking rate and weather variation account for the majority of variability associated with plant and animal production on rangelands (Van Poollen & Lacey 1979; Heitschmidt & Taylor, 1991; Gillen et al., 1998; Holechek et al. 2001; Derner & Hart, 2007). Apparently, in spite of this standpoint, two different opinions divide the grazing literature. First, proponents of rotational grazing systems contend that uneven grazing causes land degradation, reduce livestock production, and limits the effectiveness of various grazing management practices (Norton, 2003; Teague & Dowhower, 2003; Norton et al., 2004). They argue that, heavy grazing can still occur in some areas within smaller paddocks, but reducing paddock size appears to be more effective in spreading grazing pressure from increased stocking rates. Contrary, arguments in favour of continuous grazing contend that high stocking rates are unsustainable, and the negative consequences of those high stocking rates should not lead to condemnation of continuous grazing at appropriate stocking rates (e.g., Ash, Stafford & Smith 1996; Gillen & Sims 2006; Jacobo et al., 2006). Interestingly, this is in stark contrast and divergent to Norton’s (2003) notion about farmers who claim that an increase in stocking rate under some rotational grazing systems does not cause damage to the grazing environment.

Perhaps these polarised viewpoints, might suggest that grazing studies, which reject the superiority of rotational grazing systems over continuous grazing, seem to neglect the important role of grazing selection, which depends on the spatial scale of grazing. It is important to recognise that, under continuous grazing, management can control the effects of stocking rate under homogeneous grazing, but selection facilitated by heterogeneous landscapes may remain problematic. Rotational grazing systems control the distribution of grazing pressure in both space and time by ensuring regular use of the pasture. Recent empirical evidence indicates that reducing paddock size and increasing stocking rate affects grazing distribution (Barnes et al., 2008). It is therefore, surprising that empirical studies fail to show the effectiveness of rotational system compared to continuous grazing (Table 2.2, Figure 2.1). We present results of studies on the influence of stocking rate on plant responses under a grazing system.

(a) Grazing Pressure, Selective Grazing and Plant Responses

The synthesis by Briske and co-workers compared various study results and presented separately for those investigations that used similar stocking rates between grazing treatments, those that used greater stocking rates for rotational grazing (RG) than

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continuous grazing (CG), and for all stocking rates combined , and results were variable (Figure 2.1).

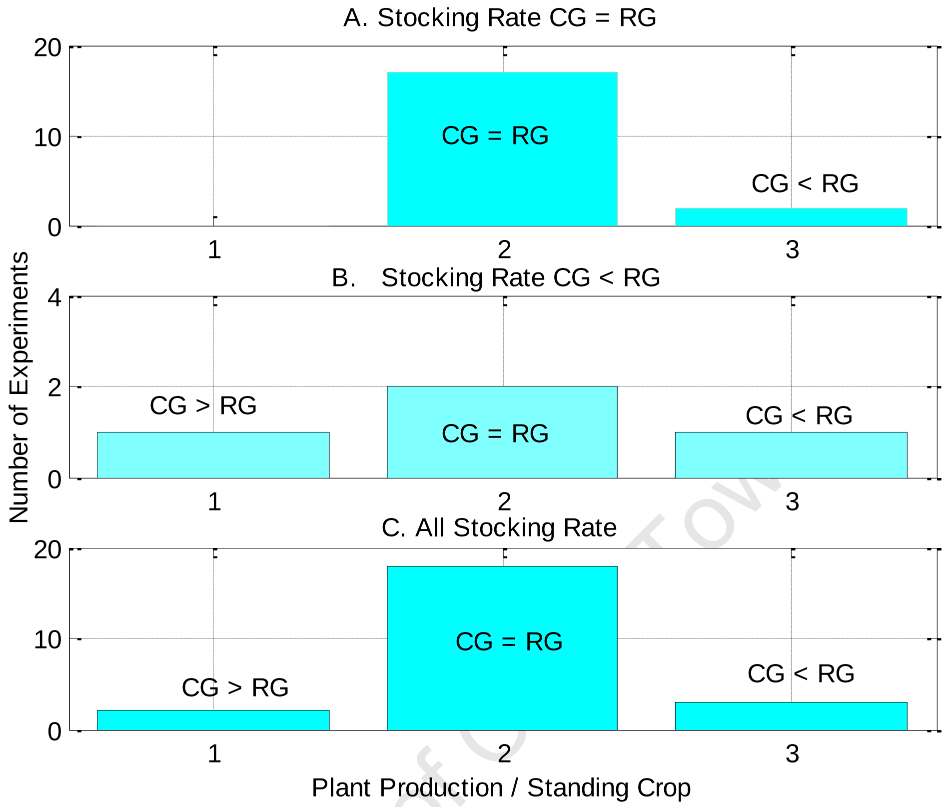

FIGURE 2.1: Number of published grazing experiments that reported significantly higher, equal, or lower plant and animal production responses for continuous compared to rotational grazing at (A) similar stocking rates, (B) higher stocking rates for rotational grazing, and (C) across stocking rates for all experiments (Data Source: Briske et al. (2008). CG: Continuous grazing, and RG: Rotational grazing. For detailed information of the experimental studies summarised here, refer to Briske et al. (2008).

By vote-count procedure, 89 % of the experiments (17 of 19) reported no differences for plant production (standing crop) between rotational and continuous grazing with similar stocking rates (Figure 2.1). Lower stocking rate for continuous than rotational grazing revealed that 75% of the experiments (3 of 4) had either no differences or greater plant production for continuous grazing. Similarly, across all stocking rates, 83% of the experiments (19 of 23) reported no differences between rotational and continuous grazing; 13% (3) reported greater plant production for rotational compared to continuous grazing, and one experiment (4%) reported greater production for continuous grazing (Figure 2.1).

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Clearly, the overall summary shows that plant responses are the same irrespective of the type of a grazing system (Figure 2.1). Particularly, several individual or group of studies have evaluated forage production in short duration grazing (SDG) compared to other grazing systems (Heitschmidt et al., 1987b; Kirby et al., 1986), and forage production at different stocking rates or stock densities within SDG (Brummer et al., 1988, Hart et al., 1988; Heitschmidt et al., 1987a; Ralphs et al., 1990). They concluded that SDG or increasing stocking rates or stock densities within SDG did not increase forage production. Surprisingly, higher stocking rates reduced standing crop due to the greater forage removal. Mathematically, Heitschmidt & Taylor (1991), as quoted by Norton (2003), have also shown that grazing pressure, defined as the forage demanded by livestock relative to the forage present in the paddock being grazed, increases under rotational grazing in proportion to the number of paddocks in the rotation.

In terms of feeding and diet selection, Gammon & Roberts (1978a) concluded that selection could not perform better by adding more camps to a rotational grazing system and that livestock followed the same selection patterns under both rotational and continuous grazing. Contrary to Gammon & Roberts (1978a), Teague & Dowhower (2003) examined the ability of rotational grazing to reduce degradation caused by patch-selective grazing in large paddocks (1800–2100 ha). The eight-paddock rotation increased herbaceous basal cover and decreased bare ground relative to continuous grazing. Both treatments exhibited improvement during favourable growing conditions, but the improvements were significantly greater in the rotational grazing treatment, where there was also less deterioration during drought (Teague et al., 2004). The most contrasting feature of these two studies could be the sizes of grazing pasture under study.

The effects of stocking rate on rangeland ecosystems, like many other disturbances, are scale dependent. For example, contrary to the studies mentioned above (e.g. Brummer et al., 1988, Hart et al., 1988, Heitschmidt et al., 1987a; Ralphs et al., 1990; Heitschmidt & Taylor, 1991), the effects of rotational and continuous grazing on plant-herbivore interactions were examined (Noy-Meir, 1976). Results showed that moderate (short) rotation, with few subdivisions and short cycles, had only minor effects on productivity, compared with continuous grazing. Intensive rotation (many paddocks and/or long cycles) resulted in a decrease in long-term productivity (in terms of plant responses) when the stocking rate was moderate and the initial plant biomass of

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the pasture high. When the stocking rate was high and the initial biomass of the pasture poor, but an ungrazeable residual was present, intensive rotation substantially increased the long-term plant productivity compared with continuous and moderate rotational grazing. Similarly, in another study, plant response for deferred-rotation grazing was superior to continuous or season-long grazing on Palouse bunchgrass ranges, mountain coniferous forest ranges, sagebrush bunchgrass ranges, and tall grass prairie ranges (Holechek et al., 1998).

Figuring out from these two case studies (Noy-Meir, 1976; Holecheck, 1998), promising results on rotational grazing have emerged. First, the studies reveal the criticality of considering a proper combination of number of paddocks, and therefore the paddock size in a rotational cycle together with stocking rate. Second, perhaps pasture characteristic could play a critical role, as various plants would respond differently from the same disturbance (grazing pressure). Stocking rate is just one of the fundamental factors controlling the outcome of grazing studies. Its effects on plant responses would depend on other factors such as timing and the period of grazing in individual paddocks. For example, using conservative stocking rates in grazing systems that involve paddocks being ‘rested’ becomes less effective when some areas of a large paddock are subject to overuse by livestock. Similarly, grazing during the early stages of plant development would seriously affect subsequent growth depending on the period of stay in individual paddocks.

(b) Animal Responses

The same recent review by Briske et al. (2008) also re-analysed animal responses only to reveal that animal production per head and per area was equal or greater in continuous compared to rotational grazing in 92% (35 of 38) and 84% (27 of 32) of the experiments, respectively. These findings are in line with findings of some individual studies irrespective of the type of range or the type of grazing system. For example, animal performance did not differ in comparing continuous, season-long, or deferred-rotation systems on Palouse bunchgrass (Skovlin et al., 1976) or coniferous mountain ranges (Holechek et al., 1987). In the tall grass prairie, individual animal performance decreased with deferred-rotation compared to continuous grazing (Owensby et al., 1973). Notwithstanding, there are examples of studies that reveal the potential results for rotational grazing systems if their design and execution can only be improved.

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A multi-paddock grazing study by Denny & Barnes (1977) and Barnes & Denny (1991) in Bulawayo at Matopos research station, as reanalysed by Norton (2003), reveal that a stocking rate twice that recommended for the district could be sustained for 5 years without adversely affecting range condition. Interestingly, as the grazing period became shorter, the stocking rate effect on animal performance was reduced. A doubling of the recommended stocking rate did not substantially reduce animal performance in a rotational grazing system with grazing periods of 5-10 days. This same reanalysis indicated that the production per head declined linearly as the rest period increased from 10 to 140 days (Norton, 2003). However, the years during which the study was conducted on Matopos were generally dry (Richardson, *pers.comm).*

The analysis presented above is perhaps what led Norton (1998; 2003) to hypothesize that a*s* a livestock enterprise moves from continuous grazing in large paddocks to rotational grazing systems with increasing numbers of small paddocks, the production per head and the corresponding production per hectare increases. This conclusion indicates a number of important factors deemed necessary in the design of rotational grazing systems. The factors include stocking rate, rainfall, size of paddocks and period of grazing in the rotational cycle. In this study, analyses of these factors and/or their combination would provide insights on how to improve the design and execution of grazing systems to improve animal production in particular.

(c) Responses of Other Variables

Proponents of short duration grazing maintain that this system benefits rangeland resources and domestic livestock production in many other ways including improved soil water infiltration, and increased mineral cycling due to animal impact. Contrary, in a brief review of the effects of grazing systems, Coughenour (1991) concluded that there are no differential benefits between short duration grazing and continuous grazing in respect of soil properties and other variables. Tests on soil properties and seedling establishment did not show any positive effects and water infiltration did not vary consistently under the continuous, rotational and short-duration grazing systems tested (Abdel-Magid et al., 1987). Thurow et al. (1986) found that water infiltration rates under short-duration grazing were lower than rates under moderately-stocked continuous grazing on bunch- or sodgrass but did not differ in oak mottes. Infiltration under heavy-stocked continuous grazing was slower than under short-duration grazing on sodgrass but not in oak mottes. However, Wood & Blackburn (1981) found no

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differences in infiltration rates between a high-intensity low-frequency system and continuous grazing under moderate or heavy stocking. Similarly, harvest efficiency, measured as the proportion of utilised to available forage did not improve by short rotation (Hetschmidt et al., 1987a). Forage quality (amount of green material) and quantity (total forage) on a short duration grazing system were not different from quantity and quality under long rotation system (Heitschmidt et al., 1987a, b, & c).

2.3.5 Limitations of Studies on Grazing Systems

The preceding sections suggest that complete denunciation of the use of rotational grazing as means to enhance plant production, reduce selection and grazing pressure is premature. Some of the studies reviewed here have comprehensively evaluated grazing systems and their findings are encouraging. Exploration of the effects of stocking rates on production represents their strong feature. Surprisingly, very few have attempted to implicitly explore how rainfall interacts with grazing pressure under grazing systems. We need to increase our knowledge about how different paddocks scheduled for grazing at different times of the growing season respond in terms of both plant and animal feedbacks. My contention is that the performance of RG would largely depend on so many factors such that under field trials, these factors can prove very problematic to control and more often easily ignored. Plant responses under any grazing management are scale dependent. Similarly, the effects of the timing of grazing and plant responses in individual paddocks do not seem to receive adequate attention. In other words, attention to the spatiotemporal changes of various response variables is critical in making important judgment about the performance of grazing management procedures. Of course, the summaries of grazing studies presented above provide sufficient evidence to suggest that neither continuous nor rotational grazing is consistently superior over the other. Yet, this notion contradicts perceptions and experiences of field practitioners who report the contrary. A recent study has concluded that the absence of a detectable grazing effect on vegetation changes may be due to overriding influences of grazing intensity, pasture size, precipitation variability, and few replicates (Mashiri et al., 2008). I examine these factors and argue for the need to reconsider them.

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a) The need to Describe Individual Paddock Responses to Various Stocking Rates

The influences of rainfall characteristics and stocking rate on grazing systems have not been exhaustively explored. For example, applicability of studies which negate the benefits of rotational grazing systems to large grazing areas and climatically variable conditions has been questioned (Norton, 2003; Barnes et al., 2008). Norton (2003) argues that Heitschmidt & Taylor's (1991) finding that increasing the number of paddocks reduces plant growth would be true in relatively small paddocks found on research stations and on commercial properties in high rainfall temperate regions. Thus, extrapolation of this finding to semi-arid areas where rainfall is relatively low may not be reasonable.

As regards the spatial aspect of grazing, animal selection is minimally affected by small-scale heterogeneity at the feeding station level, but it is profoundly affected by large-scale heterogeneity at the landscape level. Therefore, both the size and spatial arrangement of grazed patches are major components of selective grazing (Wallis de Vries et al., 1999), which conceivably must be influenced by the paddock size and period of grazing. Furthermore, Coughenour (1991) argues that detrimental grazing impacts on plants are more likely to be measured at smaller spatial and temporal scales. Over a period of one year grazed plants could compensate for their losses because limiting nutrients are recycled at a faster rate by herbivores (MacNaughton, 1979; Coughenour, 1984).

The design and execution of grazing systems cannot be ruled out as a potential factor to consider. For example, when strict schedules of grazing are followed under a rotational grazing system, the number and size of paddocks in the rotational cycle have great potential to influence outcomes of experiments. A rigid, calendar-based rotation fails to account for variations in space and time of pasture productivity, rainfall and resulting forage growth, and seasonal changes. All these arguments lead to the importance of considering spatiotemporal scale of grazing studies – the paddock size and number, and timing of grazing in the rotational cycle. The current study endeavors to explore the effects of these factors and how they influence the performance of grazing systems.

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b) Experimental Design and Inferential Statistics

Failure of some empirical studies to provide evidence about the superiority of rotational grazing system over continuous grazing or vice versa may possibly be attributable to inadequate consideration for experimental designs, and therefore inappropriate use of inferential statistics. We take cognizance of the harsh realities of funding limitations which often restrict pasture replication in grazing research on rangelands; consequently, sub-sample error has been used to estimate treatment effects or characterize populations (cf. Brown & Waller, 1986).

A number of studies do recognize that their results might have found no differences between rotational and continuous grazing because pasture replicates might have been too small to detect effects (e.g. Brown & Waller, 1986; Mashiri et al., 2008). A detailed review on the subject of replication in ecological experiments provides undoubted wide occurrence of what is termed as *pseudo-replication* (Hurlbert, 1984). It is a term which defines the use of inferential statistics to test for treatment effects with data from experiments where either the treatments are not replicated or replicates are not statistically independent (Hurlbert, 1984).

Wester (1992) suggests that *pseudo-replication* is a matter of scale and further argues that statistical analyses of single treatment studies in which samples are taken within a relatively small area can be useful in assessing treatment impacts. This argument assumes that at small spatial scales the grazing environment is relatively homogeneous, yet in any field situation two experimental units are different in every measurable property (Hurlbert, 1984). Teague & Dowhower (2003) argue that a large body of scientific evidence (e.g. Senft et al., 1985; Stuth, 1991; Bailey et al., 1996) indicates that even in homogeneous circumstances selectivity of patch occurs and increases as the area under consideration increases in size. This implies that selectivity occurs at all levels from plant to a landscape scale and therefore echoes the necessity for replicates in any grazing experiments. Sometimes a proper experimental design can be destroyed by failing to recognize what constitutes the experimental unit (Nelson & Rawlings, 1983). Without pointing at any specific study, generally there is more room for improvement in experimental design and statistical tests in studies of grazing systems. Norton (2003) gave a good example of an excellent experiment carried out at Matopos Station which yet was limited in replication (cf. Denny & Barnes, 1977). A

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single illustration may suffice to raise awareness about the potential for occurrence of this problem in studies on grazing systems (Box 1).

Box 1: A hypothetical experiment illustrating inadequate experimental design

An experiment intends to evaluate the influence of a rotational against continuous grazing on plant condition. The study commences with eight (8) paddocks and a herd of steers grazing for a week before moved to the next paddock. Another herd of steers of comparable breed graze continuously on an area of similar biophysical characteristics. At the end of the growing season samples on plant biomass are taken in a number of plots as sampling units in both the rotational and continuous grazing fields. To analyze the data a *t*-test is used to detect the difference between rotational and continuous grazing. The results indicate that there is no significant difference between plant biomass in the rotational and continuous grazing systems.

The samples taken from the rotational grazing paddocks are only sub-samples which cannot be regarded as representing the replicates of rotational grazing treatment (Box 1). In this example we need not less than 16 paddocks for the rotation. Testing for statistical significance in the example (Box 1) would be committing what Hulbert (1984) termed as *simple pseudo-replication*. The need for replication is not a rotational grazing requisite but rather a statistical requirement. If replicates are only samples from a single experimental treatment (rotational grazing/continuous grazing pasture) then replicates are not independent (Hurlbert, 1984). Possibly farmers who do not necessarily use statistical tests have yielded benefits through simple observations. Researchers use tests to provide evidence of difference but if the use of the tests do not meet important statistical assumptions the results will not match with those of the practical farmer. There is a suggestion that farmers who implement rotational grazing manage their operations well; they continually observe the condition of vegetation and animals. They will move animals if there is no available forage or animals are rapidly losing weight. Their approach is not rigid like experimental designs.

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a) Complexities of Species Compositional Change As Performance Indicators

Related to experimental designs emerges the complexity of measures of plant responses using the concepts of species compositional change. Usually, describing range condition has been the subject of lively debate in ecology (Tainton et al., 1980; Smith, 1988a; Wilson, 1989), particularly on the issue of quantitative assessment and monitoring (Soc. Range Manage. 1983; Westobv et al., 1989; Heitschmidt & Taylor, 1991). Likewise, the use of species change in grazing systems is complicated in two fundamentally different ways. Firstly, distinguishing the cause of change between the influences of rainfall and grazing effects is of particular concern. Vegetation condition in any particular year is strongly influenced by the interaction of grazing history and recent rainfall distribution (Milchunas, & Lauenroth, 1993; O'Connor & Roux, 1995). Except under particularly severe conditions, direct defoliation effects are likely to have limited inter-annual effects. Thus, measuring responses of rangelands to disturbances using changes in species composition requires consideration for spatial and temporal scales of observation (Crawley & Harral 2001; Gering & Crist, 2002; Willis & Whittaker, 2002).

For example, in the Plains of the Serengeti National Park plant species composition is unchanged on the temporal scale of decades (Belsky, 1985), raising the possibility that rotational grazing studies (e.g. Gammon & Roberts, 1977) could have been too snapshot in time to detect the hypothesized species change. Gammon & Roberts (1977) studied the effect of each treatment within one year only. Moreover, since the influence of grazing on compositional change of Savannah h grass species appears to be more dependent upon rainfall variability (O'Connor, 1994), measurement of compositional change necessitates that the demographic processes of plant species are being affected (Anderson, 2008). Notwithstanding, Mashiri et al. (2008) has recently compared changes in eight grass and three shrub categories to grazing systems (yearlong vs. seasonal rotation) with equivalent long-term stocking rates over 12 yr and 34 yr period. Grazing systems did not influence plant dynamics as shown by the lack of grazing system by year effect on all response variables in either time period. This augers well with my contention that change in species composition is not easily observable within the time scales of grazing management units.

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Secondly, measures of species change after disturbance hinges upon the concept of species diversity. Unfortunately, the effects of disturbances on ecosystems especially moderate habitat disturbance on species diversity show little consensus, with both increased and decreased diversity following disturbance being reported with approximately equal frequency (Dumbrell et al., 2008). It is not surprising therefore to find inconclusive results emerging from studies on grazing systems which employ changes in species composition (cf. Mashiri et al., 2008).

c) Grazing System Objectives, Plant and Animal Production

Early attempts, such as rest-rotational grazing, addressed the needs of plants with less regard for herbivores, while forms of deferred rotational grazing attempted to better balance the needs of plants and herbivores (Pieper, 1980; Provenza, 2003b). Surely, these two types of grazing systems have ultimately different objectives (Table 2.1). Accordingly, to assess the performance of rest-rotation requires only vegetation as an indicator, whereas the later may concurrently consider plant and animal condition as major indicators. This perhaps explains why in a single study of rest-rotation, results may indicate that plant responses to rotational grazing were appreciable, while the same study would show poor performance of animal responses. For example, rest-rotation has shown superiority over continuous and season-long grazing on mountain ranges where cattle may heavily use riparian areas under all grazing strategies (Platts & Nelson, 1989). Yet, to the contrary a different study has shown that rest-rotation grazing reduces animal production ha^{-1} and weaning weights of calves and lambs, resulting in lower profits for livestock operations. The study further showed that average daily gain was greater for calves, lambs, and ewes grazed continuously or under deferred-rotation than under rest-rotation grazing (www.asas.org/abstracts/2003abs/034, accessed, 2009). These results raise questions about standard range evaluation approaches that uncritically link contemporary range condition with contemporary animal responses.

d) Why Do Some Field Studies Fail to Demonstrate Experiences of Farmers?

Apart from the factors discussed in the previous sections, this question has been implicitly and comprehensively addressed by Teague et al. (2008b). Firstly, researchers have sub-optimally managed multi-paddock field trials expecting to provide the best possible vegetation or animal production results. They further argue that, the notion that rotational grazing can control frequency of defoliation within a grazing period is flawed

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at the scale of rotations employed in research trials (Norton 1998). Lastly, the problem of continuous grazing is associated with large paddocks which provide for patch grazing and localized degradation. Unfortunately, researchers have overlooked this important aspect. For example, 1) a big benefit of any grazing system is that it forces the manager to get out in the pastures and pay attention to what is happening a little more closely than he would if it was a continuously grazed system 2) ranchers do not maintain the lock-step approach of repeatable research study design throughout the entire study period. Rather they make adaptive management adjustments to local situations, thus confounding the repeatability requirement of science. Thus while adaptive management is a goal for rangelands with variable conditions, the benefits are hard to test using the scientific method, hence the disconnect between scientific studies and adaptive management that applies the principles of good range stewardship. Richradson (pers comm.) suggests that from observations commercial farmers who practice rotational grazing have a plan such as timing of when animal moves in or out of paddocks but they adjust these movements and animal numbers to the condition of both the vegetation and the animals. For example, if the grass is excessively defoliated then animals would be moved out of the paddock earlier than planned. Conversely in the dry season they may graze longer if forage is plentiful. Also farmers practicing this system keep records for each paddock and also use these to help with decisions.

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2.4 Increasing Our Understanding of the System

The complementary objective of this study sought to increase the understanding about how semi-arid grazing systems function. This task could not be complete until the theoretical context of this objective was revisited. Thus, this part of the review examined the key tenets of the equilibrium/disequilibrium and non-equilibrium paradigms of rangeland dynamics and interpreted their relevance to the current study.

2.4.1 Paradigms of Rangeland Dynamics

The term paradigm has been used to indicate a pool of concepts, ideas, approaches, and principles shared and used by a scientific community to define research problems and generate possible solutions (Kuhn, 1970; Capra, 1986; cited by Wu & Loucks, 1995). In view of this definition, a paradigm occupies a critical position in science by providing a model of nature within which to identify problems and interpret results (Kuhn, 1996;

Briske et al., 2003). A shift in paradigm, in the scheme of Kuhn (1970), occurs when scientists encounter anomalies which cannot be explained by the universally accepted paradigm upon which scientific progress has been made. Advances in the field of rangeland ecology have seen two conceptually competing paradigms polarized into a theoretical debate about the equilibrium and non-equilibrium dynamics of semiarid/arid rangelands. The debate relates to the applicability of the theories and related models to semi-arid rangelands where rainfall is highly variable and unpredictable (cf. Ellis & Swift, 1988; Behnke et al., 1993; Briske et al., 2003). In this debate however, the idea of disequilibrium may be as important a concept as non-equilibrium (cf. Illius & O'Connor, 2004). The subsequent sections examine the basics of these concepts.

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(a) Equilibrium Paradigm and the Range Succession Model

Several authors have described the equilibrium paradigm and its origin at length (e.g. Wu, 1995; Illius & O'Conner, 1999). The term is related to the concept of stability and they have been used as derivatives of the idea of 'balance of nature" (Pimm, 1991, 1984; Wu & Loucks, 1995). In ecology, the concept of stability and equilibrium are usually but not necessarily, considered in relation to each other. Measures of stability are many including constancy, resilience, resistance and persistency (Holling, 1973; Pimm, 1984; Wu & Loucks, 1995). Resistance refers to the capacity of a system to stay unchanged despite the presence of a disturbance. It is measured as the degree to which a variable is changed from its equilibrium point following a disturbance. Resilience is the rapidity of a system to return to its equilibrium value following a disturbance (Holling, 1973; Pimm, 1984); and persistency means the ability of a system to remain within defined limits despite perturbations. Constancy is the degree of change or invariance in system properties over a given time. By application, plants and animals are postulated to exist in some sort of equilibrium, and various models have been presented to depict an equilibrium system.

Following Walker's (1997) review, we discuss one of the earliest conceptual models of range management (Clements', 1916). Sampson (1919) first applied the concept of succession and the 'Range Succession model' to range management (. (Fig. 2.1a),

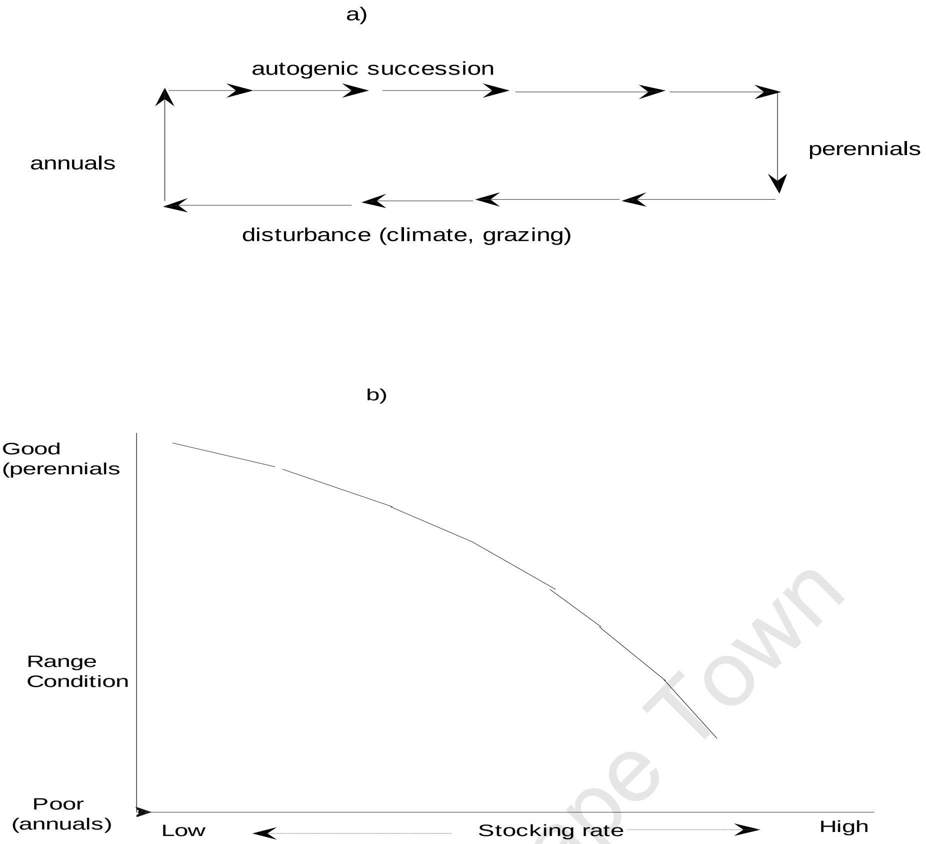

FIGURE 2.2: (a) The principles of the Clementsian succession model. The slower autogenic succession and rapid retrogression due to disturbance are seen as opposite, potentially balanced, forces. (b) The range succession model. Range condition supposedly increase and decrease smoothly in response to changes in stocking rate (After Walker, 1997).

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The key tenet of range succession stipulates the response of vegetation to grazing as a disturbance (Figure 2.1a & b). It suggests that in the absence of grazing, or on release from grazing (removal of the herbivores), the vegetation and its habitat will follow an innate tendency to move forward along a single continuum of ‘condition’ towards a ‘climatic climax’ of perennial grasses or shrubs (Figure 2.1a, b). Overgrazing, or other disturbances lead to a backward movement along the same continuum, with reduction in overall species diversity, but an increased proportion of annual plants; reduction in soil organic content, slower nutrient cycling, less rainfall infiltration and increased temperature fluctuations at the soil surface (Walker, 1997). One of the simplest models of an equilibrium grazing system was developed by May (1977). The equilibrium concept was further mathematically (Equations 2.1 & 2.2) elaborated as follows (Crawley, 1983; Richardson, 2004):

$$\frac{dH}{dt} = \lambda HV^2 \big/ \left(f + V^2\right) - dH \qquad 2.1$$

$$\frac{dV}{dt} = \beta V \left(K - V\right) \big/ K - \alpha HV^2 \big/ \left(f + V^2\right) \qquad 2.2$$

Where

H and V are measures of herbivore and vegetation abundances, respectively. K is the maximum vegetation abundance, β is the rate of increase of vegetation, α is the feeding rate of herbivores, f is the foraging efficiency of herbivores.

Equilibrium is predicted to be reached when $\frac{dV}{dt} = 0$, and $\frac{dH}{dt} = 0$.

Richardson (2004) argues that this system may oscillate before equilibrium is reached. On the other hand, Ellis & Swift (1988) suggested that equilibrium is possible or at least approachable in seasonal systems with intra-annual variation in plant growth such as wet and dry periods as long as variations between years remain small. The equilibrium paradigm is founded on these concepts making assumptions that ecosystems, populations, communities and even the entire earth possess capacity for internal regulation that are kept in stable equilibrium by predictable forces if left alone. The implication for rangeland management is that equilibrium systems return to their pre-disturbed state after disturbance (O'Neill et al., 1986; Wu & Loucks, 1995). When livestock numbers exceed the carrying capacity of the environment, overgrazing leads to degradation through loss of vegetation cover but the rangeland can also return to a pre-disturbed condition some time after reduction of livestock numbers to well below the carrying capacity. Consequently, rangeland degradation has been attributed to excessive stocking rates (Lamprey, 1983; Dean & MacDonald, 1994; cf. Figure 2.1b). According to Illius & O'Connor (2004), *equilibrium* would reach between animal populations and forage resources under stable weather conditions. Climatic variability disturbs the system leading to *disequilibrium*, which is different from *non-equilibrium*.

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Since the early part of the last century the idea of balance of nature has been out of favor among professional ecologists. Three reasons among others justify why ecologists began to criticize the equilibrium paradigm (cf. Briske et al., 2003): 1) Failure to adequately support the existence of equilibrium systems, 2) Inability to account for the dynamic behaviour of various ecological systems 3). The implication is that historical events only play a minor role in ecosystem dynamics (O'Neill et al., 1986; Wu & Loucks, 1995).

e) The Non-Equilibrium Paradigm and the Alternative Stable States Model (s)

Deciding whether equilibrium or non-equilibrium dynamics best describes any particular case can be difficult, although ecologists mostly agree that ecosystems are far more complicated and unpredictable than portrayed in the old equilibrium theory. Chesson & Case (1986) as cited by Wu & Loucks (1995) defined a non-equilibrium community as one in which "fluctuations or changes in population densities on some spatial scales are an essential part". The non-equilibrium paradigm, sometimes coined as "flux of nature" is founded on the assumption that ecosystems posses limited capacity to regulate it (Ellis & Swift, 1988; Wu & Loucks, 1995). It emphasizes on the openness, transient dynamics, and stochastic processes of ecological systems.

Apparently, Ellis & Swift (1988) recorded large variations in livestock numbers in response to low and extremely variable precipitation in Turkana District of northern Kenya, but the system remained persistent. They hypothesized that a non-equilibrium (Wiens, 1984), or biomass-vague (DeAngelis & Waterhouse, 1987), or disequilibrium (Behnke et al., 1993) in this system existed in which rainfall rather than the livestock numbers had a dominant effects upon vegetation. Consequently, Ellis & Swift proposed that livestock-plant systems with an inter-annual coefficient of variations in rainfall greater than 33% were non-equilibrium. Livestock would rather not experience biomass-dependent effects such as drought-induced mortality before animal numbers had built up to a sufficient level. Thus, Richardson et al. (2007), suggest that non-equilibrium is the special case where animal population dynamics are decoupled from those resources not associated with key factors that determine survival of the animal population over the season of plant dormancy (Illius & O'onnor, 2004). Key factors may include productive dry season grazing and supplementary feeding of concentrates and purchased forages (Illius & O'Connor, 2000).

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Briske et al. (2003), identifies three types of non-equilibrium dynamics. First, there is *persistent non-equilibrium*, analogous to *disequilibrium* in the scheme of Illius & O'Connor (2004). The other two are represented by *threshold* and *state-and-transition* models, which both specifically represent changes over time in the species (botanical) composition of the vegetation. Thresholds represent boundaries that separate multiple equilibrium states such as woody plant invasions of grassland (Briske et al., 2003).

By describing vegetation as having a single stable state, Clementsian succession may not be an appropriate model for semiarid grasslands, where variable rainfall drive vegetation change, grazing is discontinuous and shows hysteresis effects (May, 1977: Westoby et al., 1989; Friedel, 1991; Laycock, 1991). The reality in semi-arid vegetation suggests that these ecosystems if released from grazing may change very little, or it may change in ways other than those predicted under the range succession model (Walker, 1997). Mechanisms such as demographic inertia, grazing catastrophe, priority in competition, fire positive feedback and persistent change in soil conditions produce states in semi-arid vegetation that are not simply reversible by grazing management alone (Westoby et al., 1989). A theoretical alternative to Clementsian succession has been the concept of multiple stable states in ecological communities, describing vegetation dynamics as a non-linear set of alternative stable states, which differ markedly in species composition and separated by abrupt transitions in space or time. Positive feedbacks likely maintain these states between vegetation and environment – as a vegetation switch. The concept of thresholds (boundaries in space and time between two domains of relative stability, the crossing of which requires substantial intervention by management or some natural 'event') is compatible with the concept of alternative stable states (Friedel, 1991).

2.4.2 The Debate and Its Relevance to the Study

Paradigms about equilibrium and non-equilibrium dynamics are currently dominating discussions about rangeland degradation and management strategies in semi-arid and arid zones. The debate is largely an unfortunate result of confusion over terminology (Derry & Boone, 2009). Equilibrium paradigm emphasizes on biotic relationships (Egerton, 1973) based on Clementsian ideas of equilibriums between plants and herbivores around predictable stable states (Clements, 1916). This model however, suggests that attributes of the component populations, water-vegetation-herbivore

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interactions (Van de Koppel et al., 2002) and climate-ecosystem coupling (Higgins, Mastrandrea, & Schneider, 2002) may also contribute to the behaviour. On the other hand, the non-equilibrium paradigm places more emphasis on the overriding influences of rainfall and recognizing grazing as having negligible effects.

From policy and management perspective, this distinction is important in two different ways. First, if rainfall is more important than grazing and livestock do not damage vegetation, then it does not matter how many livestock graze a rangeland, because livestock cannot degrade rangelands (Ellis & Swift 1988). Second, by extension, it does not matter what kind of grazing management strategies used in livestock production if the problem of overgrazing does not result. Thus, policy and management should support pastoral families during drought to move to new pastures, but there should be no limitation on animal numbers. On the other hand, if livestock can damage vegetation by grazing, it is critically important that policy and management focus on the numbers of animals that graze a rangeland, as well as supporting the kind of management strategies, which enhance sustainable production. Based on these two different views, the debate over a shift in paradigm and suggesting the need to move from the idea of equilibrium emerged (cf. Ellis & Swift, 1988; Behnke & Scoones, 1993; Sullivan, 1996, 2002; Briske et al., 2003). Empirical studies testing these theories have been advanced.

Foremost, Illius & O'Conner (1999) synthesized a large body of information to examine the utility and appropriateness of non-equilibrium concepts in African rangelands. The assertions that herbivory has little impacts in climatically variable systems were found unjustifiable. Fynn & 'Conner (2000) examined the emerging paradigm of non-equilibrium behaviour of plant-livestock relations in a semi-arid rangeland. The notion that African Savannahs are non-equilibrium was found contradictory. Of recent, Vetter (2005) has examined the predictions and management implications of the equilibrium and non-equilibrium paradigms, and the current status of the debate. The conclusion suggested that most arid and semi-arid rangeland systems encompass elements of both equilibrium and non-equilibrium depending on different spatiotemporal scales of studying the system (cf. also Derry & Boone, 2009).

The major implication of these conclusions is that the equilibrium and non-equilibrium debate has reinvigorated the interpretation of vegetation dynamics along the entirety of equilibrium-non-equilibrium continuum (Briske et al., 2003), because grazing systems are a result of equilibrium and non-equilibrium dynamics (Derry & Boone, 2009).

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Moreover, ecosystem response to rainfall and grazing is complex, and interpretation of the response depends on variables examined (Fernandez-Giminez & Allen-Diaz, 1999). However, some workers argue that the application of non-equilibrium hypotheses to savannah h has been challenged to the extent that models indicate that herbivores in semi-arid areas are in long-term equilibrium with a subset of their resources (Illius & O’Conner, 2000).

Taking these conclusions into account, the current study perfectly aligns with the rangeland paradigms in two fundamentally different ways. First, the study explores the effects of the intensity and timing of grazing on forage production in relation to the size and number of paddocks in a rotational cycle. In line with the equilibrium theory, grazing is assumed to have negative impacts on plant production depending on the timing of grazing and stocking levels. Second, the study examines the interactive effects of variable rainfall and grazing intensity on plant production and feedbacks on animal weight. In doing so, the study interprets rangeland dynamics along the equilibrium and non-equilibrium continuum.

2.4.3 The Intermediate Disturbance Hypothesis (IDH)

The relationship between grazing and plant diversity has been further discussed in the literature by the intermediate disturbance hypothesis (Connell, 1978). Most significantly, the effect of grazing on plant diversity depends upon grazing intensity, the evolutionary history of the site, and climatic regimes (Milchunas et al., 1988). It is argued that certain levels and combinations of grazing or disturbance increase overall plant species diversity by decreasing the capacity of competitive dominants to exclude other species and by creating gaps available for occupation by other species (Archer et al., 1987; Collins 1987; Collins et al., 1987). As a result, above certain frequencies or intensities, disturbance typically lowers diversity. This phenomenon of increased diversity at moderate levels of disturbance has been termed the intermediate disturbance hypothesis (Connell, 1978). Contrary, recent literature has suggested that this mechanism may be much broader in its scope than previously recognized. Roxburgh et al. (2004) demonstrated that the IDH is a complex of different mechanism that can allow the coexistence of many species. Roxburgh used three models 1) spatial within-patch 2) spatial between-patch 3) purely temporal, to demonstrate possible coexistence mechanisms for different species at intermediate disturbance. These results point out that, mechanisms other than dispersal and competition could create the increase in

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diversity seen from disturbance. All this shows that rangeland responses to grazing management and measurement of these responses is complicated with a possibility of yielding complex results.

Nevertheless community diversity has important implications for grazing management. Growth of each species responds differently from a combination of environmental factors and management strategies. For example, fluctuations in weather cause production of individual species to vary substantially from year to year. However, production in a community as a whole is more stable, because in favourable years growth of some species causes a compensatory decrease in growth of other species (McNaughton 1977; Collins et al., 1987). Conversely, in stressful years, the loss of productivity of some species is compensated for by growth of others. As a result, changes in relative growth rates and abundances of co-occurring species tend to stabilize ecosystem processes such as primary production.

2.4.3 *Emerging Questions*

The premise of the study is that to design effective grazing management demands our understanding about the system dynamics at the appropriate scale of grazing management units. This part of the review emphasizes the importance of grazing and rainfall in rangeland dynamics. From this analysis a research question arises: Methodologically, how do we model the system in such a way that the model links responses of plant growth to variable rainfall, and the timing and intensity of grazing in a multi-paddock rotational grazing system? Given this question the next step involved a review of modelling approaches and some current models of rangelands.

2.5 A Review of Models and Modelling Approaches

Computer simulation modelling has become a methodological key skill in modern environmental research and preferred most in rangeland ecology to an approach based on monitoring for the prediction of long-term responses to different management strategies (Biot, 1993). In response to the first question (section 2.3.4), the kind of model to use for the simulation of rotational grazing should incorporate variable rainfall, plant growth and livestock feedbacks. There are numerous models in simulating semi-arid livestock grazing systems. A very comprehensive review by Tietjen & Floria (2007) has identified 41 models published between 1995 and 2005.

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The objective of their review was to assess which of the existing models are able to simulate the effects of climate change to allow for an evaluation of sustainable management strategies. This part of the review briefly presents some of existing modelling approaches and corresponding models for semi-arid rangelands. In addition, Ratze et al. (2007) undertook a broad review of existing modelling approaches in ecological modelling. For the purpose of this review, the most relevant of these approaches are revisited to explore their usefulness with regards to modelling grazing management strategies in rangelands. The model required to simulate grazing systems such as rotational grazing must be quantitative, and must be dynamical in its structure and function. The structure and processes in the model must account for the influence of rainfall variability and vegetation responses to stocking rate and diet selection by grazing animals.

(a) <u>System Dynamics Modelling Approach</u>

This approach provides a holistic view of the system by graphically showing causal relationships between different elements, and describing the nature of the relationship through update equations (Ordinary Differential Equations or difference equations). System models represent stocks and flows of information, material, or energy in differential equations linked through intermediary functions and data structures (Gilbert & Troitzsch, 2002). The assumption of this kind of mathematical models is that natural systems generally tend to evolve asymptotically toward single or multiple stable equilibria (punctual, cyclic or strange). This equilibrium paradigm leads to studies of the long-term, asymptotic behaviour of ecological systems by searching for attractors and bifurcations (Bousquet & Le Page, 2004). A classic example in rangeland ecology is Equations 2.3 and 2.4.

$$\frac{dH}{dt} = \lambda HV^2 \big/ \left(f + V^2\right) - dH \qquad 2.3$$

$$\frac{dV}{dt} = \beta V \left(K - V\right) \big/ K - \alpha HV^2 \big/ \left(f + V^2\right) \qquad 2.4$$

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The letters are as interpreted in equation 2.1 and 2.2. Equilibrium is predicted to be reached when both of the left hand sides of the two equations are zero.

However, earlier attempts to model rangeland dynamics exist (e.g. Noy-Meir, 1975). Following Noy-Meir’s work, May (1977) developed one of the simplest models of an equilibrium grazing system. Stability of grazing according to Noy-Meier (1975), exist in a dual domain of ‘discontinuous stable’ with high productivity and ‘stable state’ of low productivity. On the other hand, May (1977) describes the grazing system with multiple equilibrium states depending on the level of animal stocking rate. An alternative example is the model on competition between grasses and woody vegetation in a semi-arid environment described in Walker et al. (1981). This system has been described with bistable equilibrium: in the absence of grazing the system may be at equilibrium with high biomass of either grass or woody vegetation. Under high grazing pressure the system moves from the state in which grass dominates to one in which woody vegetation dominates.

(b) Cellular Automata Approaches

Cellular automata (CA) roots back to von Neumann (1963) and is widely used in the field of ecology. CAs are dynamic models discrete in time, space, and state (Baltzer et al., 1998). These models exist for rangeland dynamics (e.g. Li & Reynolds 1997; Wiegand et al., 1995; 1998; Witten et al., 2005), species composition (Silvertown et al., 1992), forest succession (Hogeweg, 1988; Alonso & Sole, 2000), global Land Use/ Cover Change and a host of other biological phenomena. Their advantages relate to their simplicity and flexibility, in addition to being implemented with ease on a computer. They are primarily used in relating pattern with processes in ecological phenomenon at large spatiotemporal scales. Nevertheless, these approaches may generally be difficult to link with feedbacks in secondary production (e.g. weight gain, animal population dynamics).

(c) Frame-Based Models

Frames are defined to represent distinct states of a system, which can change over time. Independent models are developed for each frame to simulate processes within that frame. Rules are developed for switching between frames. The frame based savanna model of Hahn et al (1999) was developed from the conceptual state and transition model of Westoby et al (1989). Characteristic feature of these models is that

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they simulate the effects of livestock on plant dynamics and vice-versa and accommodate variation in rainfall and its distribution within the year. Other models in this regime simulate landscape-level response of vegetation to transient changes in climate and explicitly represent the spatial processes of disturbance propagation and seed dispersal. Thus, their weakness may be that they are not easily adaptable for the implementation multi-paddocks of rotational grazing systems.

(d) Dynamic Mechanistic Models

Mechanistic models are designed to provide understanding or explanation of the system being modelled. The model must be constructed so as to represent at least two levels of the system (Thornley & France, 2007). For example, grass growth (upper level) is interpreted in terms of absorption and transpiration of water, synthesis of substrates and their allocation to different parts to the plant. Mechanistic models describe the link between some process and basic principles of cause. These models are preferred because they provide more realistic predictions, and more can be done with them in terms of analyses. They can also be used to simulate a wide range of scenarios with limited experimental data, and test the effectiveness of different grazing management strategies. For example, they have been used for the evaluation of short-term management strategies (see Richardson & Hahn, 2007). Spalinger & Hobbs (1992) draw attention to the need to develop a more mechanistic explanation of the relationship between intake rate and herbage availability for large herbivores. This is necessary in evaluation of rotational grazing systems. Nevertheless, a mechanistic approach also has its deficiencies, for it cannot consider the role in controlling intake and selection of animal behaviour, such as adaptive decisions, for which the mechanisms are not known (Parsons et al., 1994).

In this study a mechanistic model developed by described by Richardson (2000) was found very useful for some reasons. First, the model was constructed in such a way that it could be expanded to simulate rotational grazing. The present model only allows for simulation of a single paddock (continuous grazing). Second, the model structure contains a sub-module of carbohydrate reserves and roots. One of the aspects debated in studies of rotational grazing include the initial carbohydrate reserves stored in the root biomass and how they affect the initial plant growth in different paddocks scheduled for

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grazing at different times of the year. However, the model needed modifications in order to allow for simulation of a multi-paddock grazing system.

In summary, this part of the review suggests that there are different ways of modelling and different types of models for the semi-arid livestock grazing systems. Models, which relate rainfall and plant growth to animal responses such as gain in weight, would be suitable for the evaluation of grazing systems. First, noticeable plant growth and animal gain in weight take place within time period of grazing management periods of days. Paddock grazing occurs within days. On the basis of this criterion, the Savannah h model (Richardson, 2000) was identified as one of the most suitable for the purpose of this study. Details of the model will be described under Chapter 3.

2.6 The Proposed Approach

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This review sought to address the general questions posed in Chapter 1 and, subsequently identify specific research areas for the current study. The general questions investigated include (a) What are the possible factors to account for the variation between different experiments in respect of the effects of rotational and continuous grazing? (b) Which factors have received little attention, which could be considered with a modelling approach and re-evaluate rotational and continuous grazing systems? (c) Given the interaction between variable rainfall and selective grazing, what practical modifications to grazing systems are necessary in order to realize their purported benefits? It has been speculated that when experiments have not been replicated using statistical tests violates the basic assumptions for such tests. The result is that no differential effects may be detected yet drawing incorrect or incomplete conclusions. Successful and complete designs of ecological field trials are generally hampered by availability of land to provide for as many replicates as required. Beside these possible setbacks, no single study has holistically investigated grazing systems. Generally, research should be reoriented towards investigations that seek to understand the interactions between the influences of rainfall and grazing management practices. The proposal of the current study to include several indicators such as feedbacks in inter-relations between variable rainfall, soil water dynamics, belowground biomass, carbohydrate reserves, green leaf, and dry matter intake, makes it unique.

(1) Given the relationship between the size of a pasture and grazing pressure, how would the increase in number of paddocks in the rotational cycle influence plant

response under rotational grazing compared to the same pasture operating under continuous grazing?

(2) Rainfall in semi-arid/arid rangelands is one of the single most important factors influencing the dynamics of the system. How does rainfall interact with the effects of grazing to influence plant-animal interaction under both continuous and rotational grazing management procedures? How do carry over effects of the previous history of the vegetation and livestock influence current productivity?

(3) How does seasonal dynamics of soil water in a pasture under rotational grazing compare with seasonal dynamics of water in a continuously grazed pasture at the same stocking rate? How do differences in soil water under a grazing system affect plant growth in subsequent seasons?

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It has been argued that changes in plant species composition are slow in terrestrial ecosystems and are therefore complicated to use in evaluation of the performance of grazing management practices. The alternative approach is to use fast changing patterns and processes as indicators of grazing system performance. For example, various management practices, season of use, degree of utilization, and grazing systems can partially be based upon how they affect carbohydrate reserves of grasses (National Research Council, 1962). The advantage is that effects of a particular management practice can be partially evaluated in a single year by observing carbohydrate reserve levels and variations. Knowledge of the seasonal variation of carbohydrate reserves and the effects of climate and management practices on them will help pasture and range managers improve present management practices. Yet, the seasonal variation of carbohydrate reserves of many grasses under rotational grazing procedure has not been fully investigated.

However, the literature on the notion that carbohydrates reserves are important in regrowth of forage plants is at variance. Numerous authors have investigated or reviewed the role of storage carbon in forage plants (e.g. Hyder & Sneva, 1959; Weinmann, 1961; White, 1973; Trlica, 1977; Daer & Willard, 1981; Briske, 1986). The emerging conclusion is that storage carbon is remobilized after defoliation and is an important carbon source for regrowth. Contrary, a number of authors have also found poor correlation between labile carbon reserves and regrowth after defoliation, and have disputed the traditional long-term belief that long-term storage is a primary source for regrowth (e.g. Davidson & Milthorpe, 1966; Caldwell et al. 1981; Richards & Caldwell, 1985; Richards, 1986). However, observations have shown that *Themeda triandra* a species highly preferred species by herbivores does not persist under heavy continuous grazing (Ndawula-Senzimba, 1972; Foran, Tainton & Booysen, 1978). Explanation for rundown of *themeda* under grazing remained speculative until when Danckwerts (1993) suggested that it was due to carbohydrate reserve rundown associated with frequent defoliation. In prairie ecosystems, Turner et al. (2007) found that previously adopted defoliation stubble (prairie grass) height of 45 to 50 mm is suitable to maintain carbohydrate reserves at levels adequate to maintain optimal regrowth and persistence of prairie grass and orchard grass. The study further showed that while decreasing defoliation height to 30 mm may be acceptable for orchard grass, prairie grass is more sensitive to defoliation severity, with defoliation below 45 mm not recommended. This leads to the proposition that flexible grazing management strategies that allow plants a rest or deferment after defoliation are necessary for regrowth and to maintain sufficient leaf area for growth and maintenance. With this understanding the following question arises for this study to address:

(4) Carbohydrates reserves are major metabolic and storage components in grass, which may change following herbage removal. Therefore, if rotational grazing allows herbage to grow to greater abundance than continuous grazing pasture, how would the concentrations of carbohydrate reserves contained in grass growing under rotational grazing compare with carbohydrate reserves of grass under continuous grazing?

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2.7 Conclusion

Although extensively studied, the use of rotational grazing systems in rangelands renders opportunities for further research. The review concludes that findings of studies on grazing systems generally remain at variance. Evidently, appealing arguments from proponents of grazing systems suggest that rotational grazing can enhance both plant and animal production. The failure by previous efforts to unravel such potentials requires that grazing studies pay more attention than ever to a multitude of interactive factors. These include the sufficiency of experimental designs and aptness of using inferential statistics. Besides, proper combination of stocking rates, paddock size and paddock numbers, the timing of grazing are critical for desired outcomes of studies on grazing systems. Published research has given a cursory attention to these factors and, therefore it remains premature to make conclusive judgements, which reject the use of rotational grazing systems as an appropriate or valid system. Nevertheless, the current study approaches the problem with modelling, and therefore envisages overcoming the potential difficulties inherently associated with field trials. Experimental designs rarely make it possible to make sufficient account for the complex interactions involved in rangeland responses to a management strategy.

The review on paradigms and related theories suggests that the equilibrium theory mostly recognises the role of biotic factors, such as plant-animal interactions making its applicability to semi-arid rangelands inadequate. The non-equilibrium theory focuses on the influence of rainfall on rangeland dynamics and disregards the impacts of increased grazing pressure. Studies have shown that semi-arid/arid ecosystems exhibit both equilibrium and non-equilibrium behaviours. The study embraces these principles by proposing further understanding of the rainfall-plant-animal interactions, thereby taking cognisance of the significance of both paradigms.

Several models and modelling approaches are available, the choice of which depends on the problem under consideration. The savannah mechanistic model was suitable for this study, because of its appealing structure and functionality, such as the linkages between rainfall-water-plant-animal responses, which are relevant in semi-arid systems. Lastly, so far the current review and most reviews on studies of grazing systems have employed narrative and semi-quantitative approaches (e.g. Briske et al., 2008). Besides, the research questions presented in this chapter, synthesis studies should step further to re-analyse grazing systems with more quantitative approaches. Of course, meta-analysis has received some criticism but most of these have been resolved in the literature (Osenberg et al., 1999a & b).

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Chapter 3

Adapted Version of the Savannah Model: A Description

3.1 Introduction

Following the detailed review of grazing studies, theories and models, the second objective was to refine the savannah temporal mechanistic model of Richardson (2000). The model structure was adjusted to be able to simulate a multi-paddock grazing system. This chapter describes the conceptual structure of the model comprising modules of rainfall-soil-water dynamics linked with grass growth diet selection and food intake by growing steers. The model allows investigation of the influence of grazing management practices, seasonal and inter-annual variability in rainfall on the dynamics and productivity of savannah rangeland. Management practices of interest may include stocking rate adjustments; timing of grazing and the rotational/continuous grazing systems.

3.2 Site-Specific Characteristics

The construction of the model, especially the plant module was based on Dye's (1984) study, which was conducted in Zimbabwe at Matopos Research Station. A brief description of the site-specific is therefore necessary. However, detailed descriptions are provided in Dye (1984) and further captured in Richardson (2000). The range is at an altitude of 1420 m above sea level receiving the mean annual rainfall of 615 mm varying from 264 to 1261 mm. The soil has been classified as a shallow moderately fertile sandy clay loam derived from basement schist. The vegetation is an *Acacia* tree-bush savannah h (Rattray, 1961/62) comprising tree species of *Acacia karoo, A. nilotica* and *A. rehmanniana*. Broadly, Rattray (1957) classified the vegetation as *heterpogon*-other species grassland. Dominant grasses include *Heteropogon contortus, Cymbopogon pospischilii* and *Themeda triandra* (Dye & Spear, 1982; Dye, 1984).

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3.3 Model Conceptualization

3.3.1 The Multi-paddock System

A rotational grazing is considered where in each of *T* consecutive time periods a mob of animals grazes one of N_P paddocks before moved to the next paddock. The number of animals may be varied during the grazing season. Grazing schedules are designed in such a way to allow comparison between the rotational and continuous grazing systems. With a continuous grazing system, animals are placed in a camp at the beginning of the season (September, 1) and remain there for the entire grazing period of each year. Alternatively, the rotational grazing operation consists of options on parameters to schedule grazing events to match the period of grazing within a paddock. Since the area of the rangeland is fixed, N_P can vary according to the following computational procedure:

$$N_P = \frac{D_{rest}}{D_{cg}} + 1$$

Where

D_{rest} : Average number of grazing days between grazing periods.

D_{cg} : Average number of days per grazing period.

3.1.2 Necessary Assumptions

- The model employs a functional approach instead of a species-based approach as it can be assumed that the dynamics of the grassland at either paddock or whole farm scales could be explained by the average biological attributes (functional traits) of the plant community making up the grassland (cf. Jouven, Carrere & Baumont, 2006).

- The initial herbage in each paddock is the same and animals are shifted each time period regardless of the post- or pre- grazing mass and visit the paddocks in the same order in each rotation.

- The average grazing pressure in each paddock is assumed to remain constant and initially set at a predetermined stocking rate at the beginning of the growing season

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- The state of each paddock is expressed in terms of soil water, grass biomass and animal responses. Consideration for these factors has been based on established knowledge about the general dynamics of semi-arid rangelands discussed in the next subsection.
- Removal of soil water from each horizon is a function of green leaf biomass and of the amount of water stored in that horizon. Losses due to interception by plant, the references are all concerned with semi-arid regions with relatively low herbage yields as is the current study. If grass above ground biomass is very high as in temperate regions or irrigated pasture then interception losses may be significant

3.3.3 Rainfall and Soil Water

Soil water dynamics influences available moisture in savannah systems and plays a great role in determining biological activity. Rainfall often occurs in irregular pulsations of short-lived storms (Griffiths, 1972; Dye, 1984). Besides infiltration and runoff, water dynamics in savannah models incorporate two key processes of evaporation and extraction of the water demanded for transpiration (e.g. Dye, 1984; Walker & Langridge, 1996). These models use a three-soil layer approach, whereby evaporative losses are assumed to occur only from the top soil through potential evapo-transpiration with the influence of vegetation cover. The current model disregards the effects of intercepted water on grounds that its effect on soil moisture is counteracted since the evaporation of the intercepted water from the vegetated surface reduces the amount of soil water that is lost via evaporation from the soil surface and via transpiration (Walker & Langridge, 1996). Transpiration is calculated in all the three soil horizons depending on plant available water.

In the water balance sub-model, rainfall is partitioned between run-off, storage in the soil profile and loss by deep drainage. These processes are modelled as instantaneous events. Soil moisture decreases continuously as a result of evaporation and of transpiration, which is represented as a function of soil moisture and the weight of green leaf. Dye’s model has been modified to allow for differences in soil water storage capacity and infiltration characteristics. The parameters of the infiltration equation were determined empirically for a specific soil type (red clay soil derived from basement schist at Matopos (see Dye', 1984).

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3.3.4 Vegetation Structure

The structure of semi-arid Savannah is recognized as a competitive grazing system comprising grasses and woody plants as described in Walker et al. (1981). The current model however, considers "semiarid savannah" which due to persistence of disturbances tends to be dominated by grasses and therefore follows the concept of the rangeland and savannah models (Scholes & Archer, 1997; Richardson & Hahn, 2005). Woody plants are ignored as this savannah condition is assumed to comprise widely scattered mature trees (e.g. Hahn et al., 1999). The purpose is not to address the tree-grass coexistence puzzle as favored in most savannah studies (e.g. Sarmiento, 1985; Scholes & Archer, 1997; Higgins et al., 2000), but rather to examine the natural impact of rainfall variability on grass production simulated under a continuous grazing but evaluated against a rotational grazing system. The conceptual basis of the vegetation sub model generates the causative relations between the structural characteristics of grass and the herbage intake of grazing animals, selection and in the management of grass forage and grazing animals.

Computation of grass is done on culms, green leaves, inflorescences, dead leaves, old dead leaves, roots and substrate, and carbohydrate reserves. According to White (1973), carbohydrate reserves are used by plants as substrate for growth and respiration. Adequate carbohydrate reserves are important in growth after herbage removal when the photosynthetic production is inadequate to meet these demands.

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3.3.5 Animal Responses to a Grazing System

To investigate the dynamics of animal production, a sub model of steers is included. As it affects animal performance (Waldo & Jorgensen, 1981), dry matter intake is the most important variable in this sub model. The model calculates on a day-to-day basis the selective forage intake at plant scale and links with changes in animal weight in relation to energy intake. Grass forage depletion by animal intake initiates feedbacks on herbage growth reflected to a plant growth sub model. Animal weight is calculated based on net energy balance, defined as the difference between net energy intake and net energy requirements for maintenance. Feeding systems, such as ARC (1980), CSIRO (1990), and the Cornell System (Fox et al., 1992) adjust the requirement of maintenance in grazing animals with information obtained in experiments carried out indoors in calorimeters or respiration chambers. These approaches regard walking to considerably increase energy expenditure of grazing animals (Clapperton, 1964; Graham, 1964; Ribeiro et al., 1977), although several workers have not found a negative effect on animal production or feed intake due to the activity of walking (Lamb et al., 1979; Nicholson, 1987; Thomson & Barnes, 1993; cited by Gemeda et al., 1995).

Notwithstanding, grazing animals have an extra daily maintenance requirement due to the demand of energy for the physical activities of forage intake and walking. The net energy balance determines weight and condition gain or loss with feedbacks on energy requirements and intake capacity. Grazing systems used and controlled by man, from intensive pastures to extensive range, are generally considered as a special case of 'predator-prey systems' (Noy-Meir, 1975). The logistic equation describes the time dependence of grass growth processes. Where dimensional units are not specified, reference can be made to Appendix C. The soil plant module and links to plant growth and finally its utilization and response by cattle (Figure 3.1).

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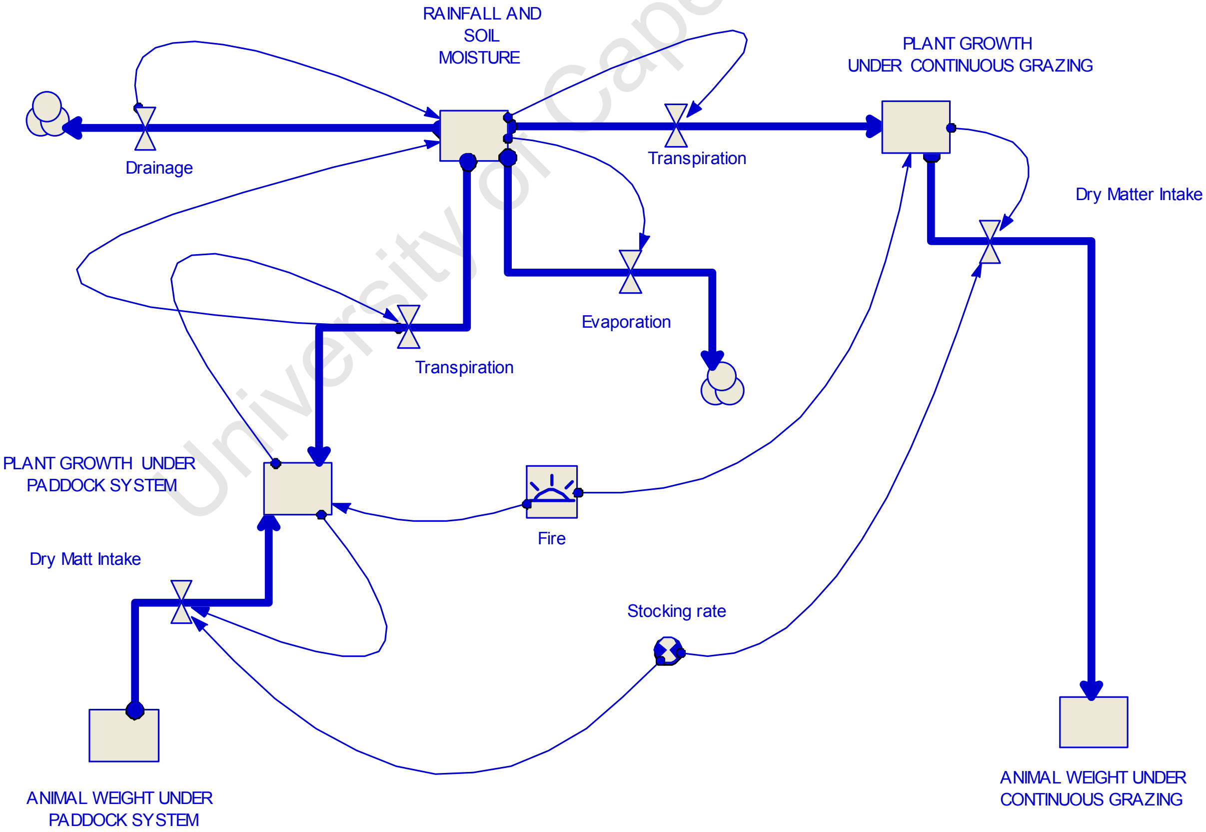

FIGURE 3.1: A generalized conceptual representation of the model structure depicting the predicted dynamics of grass growth with rainfall and plant-animal feedbacks under two different grazing systems. The bold arrows with notches indicate feedbacks of various processes and management practices on the rangeland. The diagram was drawn in simile software 5.3 version with different meanings attached.

3.4 The Water Balance Module

The objective of this sub-model is to simulate on a daily basis the changes in the amounts of water in different parts of the soil profile at both the paddock and farm scale. The module is developed to simulate effective rainfall that recharges soil moisture for a specific period of time. The soil moisture module simulates changes in the amounts of water in three different layers at different depths of 0 – 10 cm, 10 – 40 cm and 40 – 90 cm, respectively (Figure 3.2). The processes affecting the water store at the different layers include transpiration, evaporation and drainage. The method for estimating rate of transpiration of water by grass follows the approach proposed by Dye (1984).

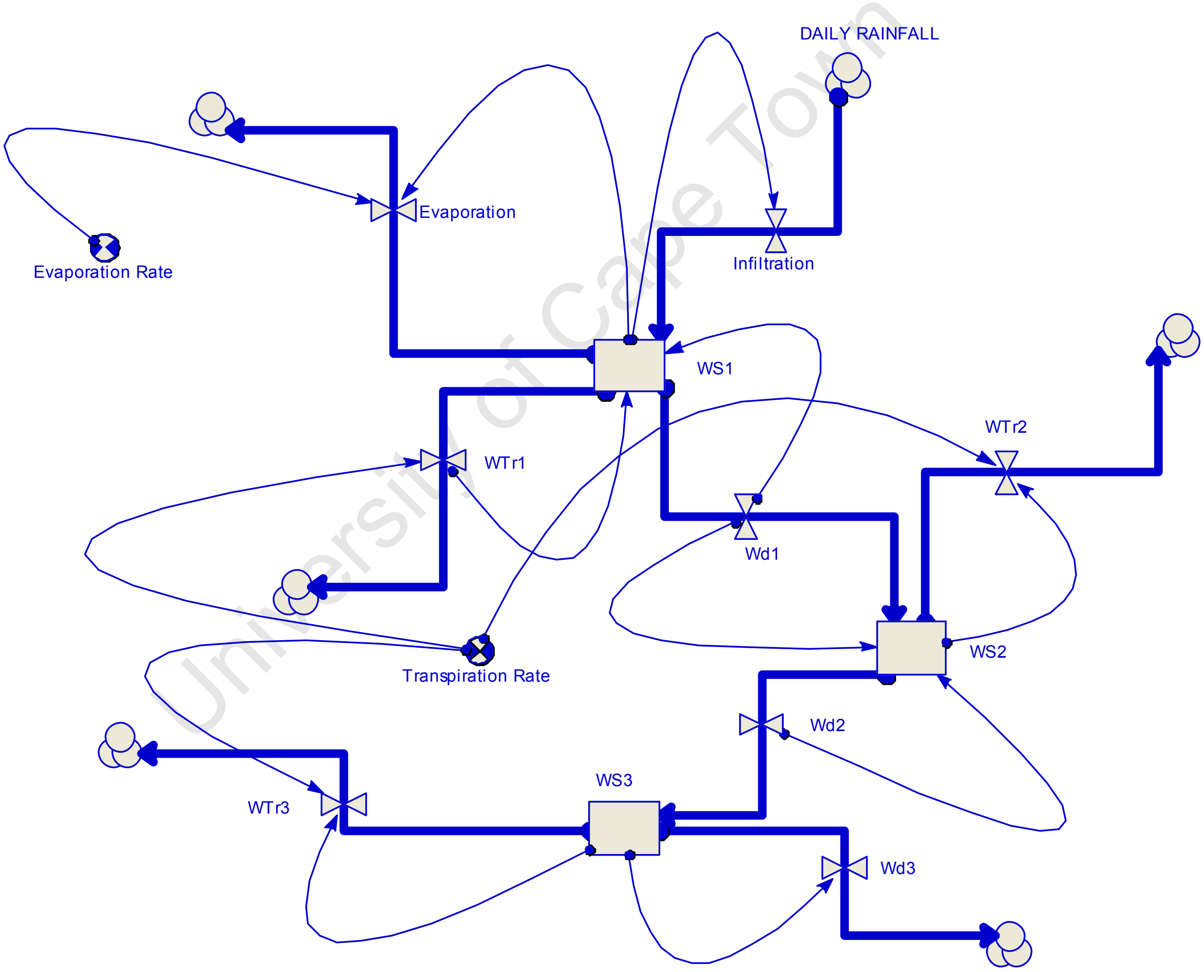

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FIGURE 3.2: A simplified conceptual structure of soil moisture module indicating the processes affecting water dynamics in three different horizons (WS1, WS2 & WS3). Water stored in A horizon (WS1) is influenced by infiltration, evaporation, water lost through drainage (W_{d1}) and transpiration (W_{Tr1}). W_{S2} and W_{S3} are influenced by transpiration (W_{Tr2}) and W_{Tr3}, drainage (W_{d2}) and W_{d3}, respectively.

Evaporation and drainage reduce the amount of stored water in the first 10 cm of the soil stratum while the deeper layers are affected by transpiration and drainage. Rate of transpiration is dependent on both shoot and green leaf, maximum evaporation from an open pan, and the total amount of water stored in the soil profile. The difference between rainfall and infiltration is assumed to be run-off. The effects of rainfall intensity, present soil moisture and plant cover on infiltration are not considered as interception of water by plant cover is negligible for savannah (Dye, 1984; Scholes & Walker, 1993; Walker & Langridge, 1996). Quantitative specifications of the rainfall, infiltration and run-off processes are based on a quadratic function derived from the experimental study of Dye (1984) for the Matopos site. The process proceeds as follows:

3.4.1 Rainfall and Infiltration Process

In semiarid regions, the partitioning of precipitation into surface runoff and infiltration is highly variable in space and time. Rainfall and infiltration are modeled as sporadic events occurring each day in a paddock. When rain falls new values for each of the water stores in a paddock are calculated at the start of each day. The rain falling in each paddock (falling on paddock, *R* (mm)) is partitioned between infiltrations into each paddock W_{in} and run-off and handled as follows:

$$W_{in} = \begin{cases} R & R < 12 \\ 1.05R - 0.005R^2 - 0.4 & otherwise \end{cases} \qquad 3.1$$

Rain water in paddock *P*, infiltrates into the soil and stored in the different horizons as W_{S1}, W_{S2}, and W_{S3}, respectively (Figure 3.2). Each horizon in a paddock can hold a maximum of $\mathrm{W_{Astmax}}$, $\mathrm{W_{Bstmax}}$ and $\mathrm{W_{Cstmax}}$, respectively. Once filled up to the maxima, the excess water drains into the next horizon. When all the three horizons are filled up, the excess water is lost through deeper drainage. The relationship between stored water and drainage is predicted as follows:

$$W_{drainA} = \begin{cases} 0 & (W_{Ast} + W_{in}) \leq W_{Ast\max} \\ W_{Ast} + W_{in} - W_{Ast\max} & (W_{Ast} + W_{in}) > W_{Ast\max} \end{cases}$$

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Thus

$$W_{Ast} : \quad = W_{Ast} + W_{in} - W_{drainA} \qquad 3.2$$

$$W_{drainB} = \begin{cases} 0 & (W_{Bst} + W_{drainA}) \leq W_{Bst\max} \\ W_{Bst} + W_{drainA} - W_{Bst\max} & (W_{Bst} + W_{drainA}) > W_{Bst\max} \end{cases}$$

Thus

$$W_{Bst} \quad : \quad = \quad W_{Bst} \quad + \quad W_{drainA} \quad - \quad W_{Bst\max} \qquad 3.3$$

$$W_{drainC} = \begin{cases} 0 & (W_{Cst} + W_{drainB}) \leq W_{Cst\max} \\ W_{Cst} + W_{drainB} - W_{Cst\max} & (W_{Cst} + W_{drainB}) > W_{Cstmx} \end{cases}$$

Thus $W_{Cst} : \quad = \quad W_{Cst} + W_{drainB} - W_{Cst\max}$ 3.4

3.4.2 Evaporation and Transpiration

The rate of depletion of quantities of soil water results from evaporation and transpiration rates. However, evaporation exclusively depletes water from the upper soil horizon, whereas transpiration affects all the three layers. Using Equations (3.2-3.4), soil water depletion in the different soil strata is respectively modeled as a continuous process described by first order differential functions as follows.

$$\frac{dW_{Ast}}{dt} = -\omega_E \, \mathrm{W}_{\mathrm{Epot}} - \frac{W_{Ast} W_{Potrr} k \psi_{Ast}}{(W_{Ast} + 0.36 W_{Bst} + 0.25 W_{Cst})} \qquad 3.5$$

$$\frac{dW_{Bst}}{dt} = -\frac{W_{Bst} W_{Potrr} k \psi_{Bst}}{(2.8 W_{Ast} + W_{Bst} + 0.7 W_{Cst})} \qquad 3.6$$

$$\frac{dW_{Cst}}{dt} = -\frac{W_{Cst} W_{Potrr} k \psi_{Cst}}{(4 W_{Ast} + 1.4 W_{Bst} + W_{Cst})} \qquad 3.7$$

The actual rate of evaporation ($\omega_E \, \mathrm{W}_{\mathrm{Epot}}$) from Equation 5 is predicted as follows:

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$$\omega_E \ \mathrm{W}_{\mathrm{Epot}} = 0 \qquad\qquad W_{Ast} \le 5$$

Adopting Dye's (1984) approach, the *potential* rate of evaporation from the soil depends on available shoots (live and dead grass). This relationship between shoot and potential evaporation (W_{Epot}) is described as follows:

$$W_{Epot} = \begin{cases} \dfrac{E_{pan}}{7} & G_{shoot} \le 0 \\ \dfrac{E_{pan}}{7}\left[1.0 - (4.22x10^{-2} + 1.537\log G_{shoot})\right] & otherwise \end{cases} \qquad 3.8$$

ω_E : Fraction of potential evaporation related to the amount of water stored in the topsoil is computed as follows:

$$\omega_E = \begin{cases} 0 & W_{Ast} \le 16 \\ 3.75x10^{-2}W_{Ast} - 0.6 & 16 < W_{Ast} \le 24 \\ 4.667x10^{-1}W_{Ast} - 10.9 & W_{Ast} > 24 \end{cases}$$

$\mathrm{G}_{\mathrm{shoot}}$: the sum of all above ground biomass

In equations 3.5, 3.6 and 3.7:

$$\psi_i = \begin{cases} 1 & \phi_{smi} > 1 \\ 0 & \phi_{smi} < 1 \\ \phi_{smi} & otherwise \end{cases} \qquad 3.9$$

ϕ_{smi} : Soil moisture index related to the total amount of water stored in the three horizons of the soil profile.

$$\phi_{smi} = 0.043W_{tot} - 3.73$$

Where

W_{tot} : the total volume of soil water is computed as

$$W_{tot} = W_{Ast} + W_{Bst} + W_{Cst}$$

$\mathrm{W}_{\mathrm{Potrr}}$: The rate of transpiration in is also a function of green leaf and maximum evaporation from an open pan (Dye, 1984). It is expressed as:

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$$W_{Potrr} = G_{gl} \frac{E_{pan}}{7} k \qquad 3.10$$

k : variable parameter for potential transpiration rate as a result of change in green leaf biomass. Thus, the potential transpiration rate decreases as green leaf biomass in the paddock increases:

$$k = \begin{cases} 0.018 - (1.7x10^{-4} G_{gl} & G_{gl} < 78.1 \\ 0.0048 - (4.2x10^{-6} G_{gl} & otherwise \end{cases}$$

3.5 Substrate Production and Plant Growth Module

In both rotational grazing and continuous grazing systems, grass sward was partitioned into nine components of biomass (G_i). All grass structures are in g m^{-2} of measurement.

Where

G_{gl} : green leaves
G_{dl} : dead leaves
G_{odl} : old dead leaves
G_r : roots
G_{cu} : culms
G_{dcu} : dead culms
G_{inf} : inflorescence
G_{dinf} : dead inflorescences
G_c : reserved carbohydrates

Figure 3.3 displays the components and processes affecting various grass structures and substrate production.

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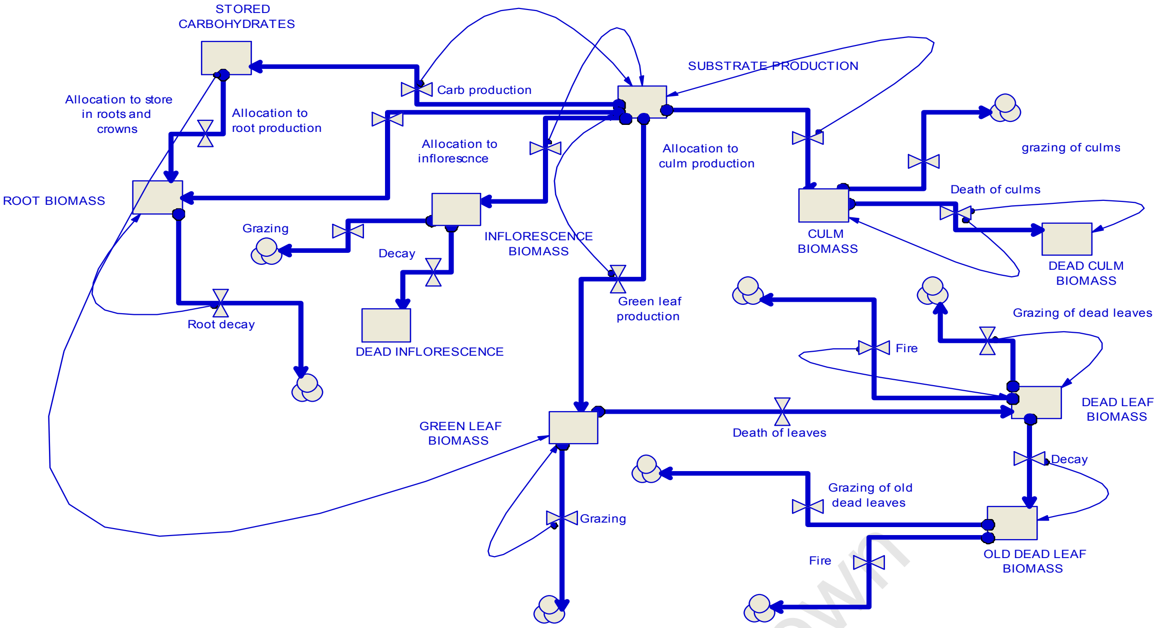

FIGURE 3.3: Conceptual representation of substrate production and allocation to various parts of grass structures. Growth of different grass structure is affected by various processes with positive and negative feedbacks illustrated by the bold and finer arrows.

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3.5.1 Production and Allocation of Substrate

Grass plants in general produce substrate and allocate to its constituent structures. The rate of change in substrate results and computed as follows:

$$\frac{dG_{su}}{dt} = \frac{\psi G_{gl} W_{Pottr} P_{seff}}{humid} - \left(G_{gl,gro} + G_{\inf,gro} + G_{r,gro} + G_{cu,gro} + G_{c,gro} \right) \qquad 3.11$$

Where

W_{Pottr}, ψ and G_{gl} : as defined under Equations 3.6-3.10.

The rate of change in substrate results from utilization for growth by various grass components computed as follows:

<u>*Green Leaf Growth*</u>

$$G_{gl,gro} \quad = \quad \frac{\mu_{gl} G_{gl} \left\{ 1 - \left(\frac{G_{Gl}}{G_{Gl,\max}} \right)^{\theta_{Gl}} \right\}}{\left(1 + \frac{G_{Gl,Ksu}}{G_{su}} \right)} \qquad 3.12$$

Where $G_{Gl} = G_{dl} + G_{gl}$

Carbohydrate Reserves accumulation

$$G_{c,gro} \quad = \quad \frac{\lambda_{c_{st}} G_r \left(G_{c,\max} - G_c \right)}{\left(1 + \frac{G_{c,Ksu}}{G_{su}} \right)} \qquad 3.13$$

If $G_c \leq 0$, $\quad G_{cc} = 0$

Rate of Root Growth

$$G_{r,gro} \quad = \quad \frac{\lambda_r G_r \left(1 - \frac{G_r}{G_{r,\max}} \right)}{\left(1 + \frac{G_{r,Ksu}}{G_{su}} \right)} \qquad 3.14$$

The Rate Of Culm Growth

$$G_{cu,gro} \quad = \quad \frac{\lambda_{cu} G_{cu} \left\{ 1 - \left(\frac{G_{cu}}{G_{cu,\max}} \right)^{\theta_{cu}} \right\}}{\left(1 + \frac{G_{cu,Ksu}}{G_{su}} \right)} \qquad 3.15$$

The Rate of Inflorescence Growth

$$G_{\inf,gro} \quad = \quad \frac{\mu_{\inf} G_{\inf} \left\{ 1 - \left(\frac{G_{\inf}}{G_{\inf,\max}} \right)^{\theta_{\inf}} \right\}}{\left(1 + \frac{G_{\inf,Ksu}}{G_{su}} \right)} \qquad 3.16$$

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Where

λ_i : the grass structure biomass intrinsic growth rate

$G_{i,\max}$: final asymptotic mass of a grass structure. This limiting size is imposed by environmental factors, basically substrate (G_{su}), space, soil moisture limitations.

θ_i : represents biomass intrinsic factor that describes how the rate $\lambda_i G$ decreases as $G_{i(t)}$ increases. That is, if $\theta_i > 1$, $\lambda_i G_i$ has a slow decrease, if $\lambda_i G_i < 1$, $\lambda_i G_i$ has a faster decrease and if $\theta_i = 1$, the rate $\lambda_i G_i$ varies linearly with $G_{i(t)}$.

3.5.2 Dynamics of Various Grass Structures

Grazing and decay processes reduce above ground structures (Figure 3.4). The rate of removal of material by grazing is primarily a function of stocking rate, defined as the number of animals of a specified class or animal units/unit area of land over a specified period.

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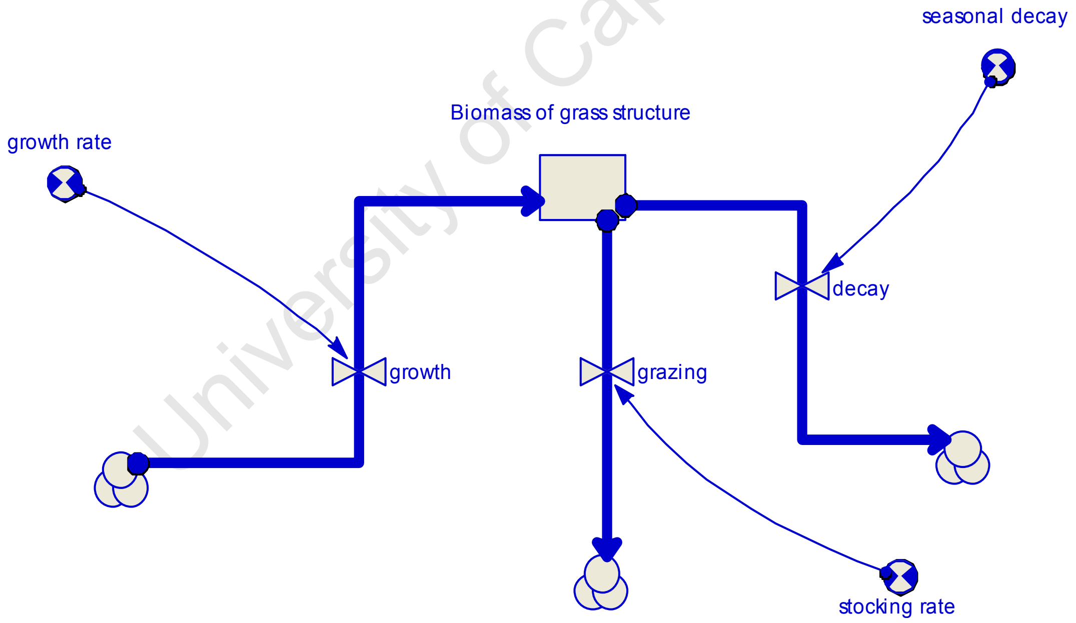

FIGURE 3.4: Generalized representation of changes in above-ground grass structures as influenced by grazing and decay processes. The rate of change in each biomass structure is influenced by stocking rate, growth rates and decay processes.

Stocking rate often affects quantity of available forage but the relative effect varies over time and space. Assuming forage quality in each paddock remains uniform, the rate of removal by grazing from each part of the grass (G_i) depends on availability and preference. As such, the rate of intake on a daily basis is modeled as a function of digestibility, biomass and diet selection. Diet selection is calculated using the concept of preference coefficients developed by Orsini (1990). Denoting the rate of removal of grass structure in each paddock as $G_{i,\ gr}$. Computation of the rate consumption of each grass structure G_i can be generalized as:

$$G_{i\,,\,gr} = \frac{D_{mi}\,.G_i \rho_i S_r}{\sum \rho_i G_i}$$

Where

$i = gl, dl, odl, cu, dcu\ inf, dinf$

$S_{r:}$ Stocking rate in a given paddock or the whole farm.

ρ_i : A preference coefficient for grass structure G_i

Dmi : daily dry matter intake for an individual animal calculated for either the entire farm or at a paddock scale. However, *Dmi* is a temporary variable to be defined later under animal sub model section

Unlike grazing, the process of decay depends on season of the year and therefore assigned a temporary variable switching between rainy and dry seasons. However, the effects of harvester termites (*Hodotermes spp.*) are ignored since the condition of the soil and vegetation on the site was not favorable for their activities.

Let $G_{i,\ dec}$ be the rate of removal of structure G_i by decay. The computation follows:

$$G_{i,dec} = Dec_{fr} G_i$$

Where

G_i : G_{dl}, G_{odl}, G_{cu}, G_{inf} , G_{dcu} and G_{dinf}

fr_{dec} :the proportional decay of structure G_i

$Dec_{fr} = Dec_{rain}$, $gr_{dys} < 60$;

$Dec_{fr} = Dec_{dry}$, otherwise;

Where

Dec_{rain} : proportion of decay during the rainy season

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$\mathrm{Dec}_{\mathrm{dry}}$: proportional decay for the dry season

$$\frac{dG_{gl}}{dt} = \begin{cases} \mu_{gl} G_{gl} \dfrac{\left\{1 - \left(\dfrac{G_{Gl}}{G_{Gl,\max}}\right)^{\theta_{gl}}\right\}}{1 + \dfrac{G_{gl,Ksu}}{G_{su}}} + \mathrm{q}\,\kappa\,\mathrm{G_c} - \left(Dec_{fr} G_{gl} + \dfrac{Dmi G_{gl} \rho_{gl} S}{\sum \rho_i G_i}\right), & when \quad paddock \quad grazed \\ \mu_{gl} G_{gl} \dfrac{\left\{1 - \left(\dfrac{G_{Gl}}{G_{Gl,\max}}\right)^{\theta_{gl}}\right\}}{1 + \dfrac{G_{gl,Ksu}}{G_{su}}} + \mathrm{q}\,\kappa\,\mathrm{G_c} - Dec_{fr} G_{gl} & when \quad paddock \quad rests \end{cases} \qquad 3.17$$

Green Leaves

The rate change in green leaf (G_{gl}) biomass is a function of producing grass reserved stored carbohydrates (G_c) the rate of consumption by grazing animals (Dmi) and rate of removal by decay (Dec_{fr}). These processes are described as follows:

Where

$\mathrm{q}\,\kappa\,\mathrm{G_c}$: Accumulation of carbohydrate reserve in the green leaf

Production of carbohydrate reserves in green leaves depends on the period of growth (days) since initiation of growth and minimum amount of green leaf biomass produced.

$\mathrm{q}\,\kappa\,\mathrm{G_c} = 0$: Before growth commences and growth period ($\mathrm{gr}_{\mathrm{dys}}$) of less than 120 days when G_{gl} is still below a certain minimum leaf amount of 60.0 g m^{-2}

q & κ : accumulation parameters for carbohydrate reserves

Dec_{fr} : The fractional rate at which green leaf undergoes senescence

$$Dec_{fr} = \begin{cases} 0 & G_{shoot} < 20 \\ 1.71x10^{-3} & gr_{wks} < 18 \\ 1.1x10^{-4}\, gr_{wks} - 2.86x10^{-4} & otherwise \end{cases}$$

$$Dec_{fr} = \begin{cases} 10.57 - 0.87(W_{S1} + W_{S2} + W_{S3}) G_{gl,die} & (W_{S1} + W_{S2} + W_{S3}) < 110 \\ G_{gl,die} & otherwise \end{cases}$$

Carbohydrate Reserves

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The maximum potential for the accumulation of carbohydrate reserve is directly related to the biomass of roots. The rate of accumulation also depends on leaf biomass and age. The prediction follows:

$$\frac{dG_c}{dt} = \mu_c G_r \frac{\left(G_{c,\max} - G_c\right)}{\left(1 + \frac{G_{r,Ksu}}{G_{su}}\right)} - G_{c,dep} G_c \qquad 3.18$$

Where

$G_{c,dep}$: A parameter for the rate of depletion of carbohydrate reserves

$\mu_{c_{st}}$: Parameter for the intrinsic rate of accumulation of carbohydrate reserves

$G_{c,\max}$: maximum saturation value for accumulation of carbohydrate reserves

$G_{c,dep} G_c = 0$, $gr_{dys} < 120$ and $G_{gl} < G_{gl,\min}$

Where

$G_{gl,\min}$: minimum green leaf biomass

Culms

$$\frac{dG_{cu}}{dt} = \begin{cases} \mu_{cu} G_{cu} \dfrac{\left\{1 - \left(\dfrac{G_{cu}}{G_{cu,\max}}\right)^{\theta_{cu}}\right\}}{\left(1 + \dfrac{G_{cu,Ksu}}{G_{su}}\right)} - \left(Dec_{fr} G_{cu} + \dfrac{DmiG_{cu} \rho_{cu} S}{\sum \rho_i G_i}\right) & grazed\ paddock \\ \mu_{cu} G_{cu} \dfrac{\left\{1 - \left(\dfrac{G_{cu}}{G_{cu,\max}}\right)^{\theta_{cu}}\right\}}{\left(1 + \dfrac{G_{cu,Ksu}}{G_{su}}\right)} - Dec_{fr} G_{cu}, & resting\ paddock \end{cases} \qquad 3.19$$

Dead culms

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$$\frac{dG_{dcu}}{dt} = \begin{cases} -\left(Dec_{fr}G_{dcu} + \dfrac{DmiG_{dcu}\rho_{dcu}S}{\sum \rho_i G_i}\right), & \text{grazed paddock} \\ -\quad Dec_{fr}G_{dcu}, & \text{resting paddock} \end{cases} \qquad 3.20$$

Dead Leaves and Dead Old Leaves

Production of dead leaves results from senescence of green leaves. Once produced, dead leaves reduce by grazing animals and decay processes (Figure 3.4).

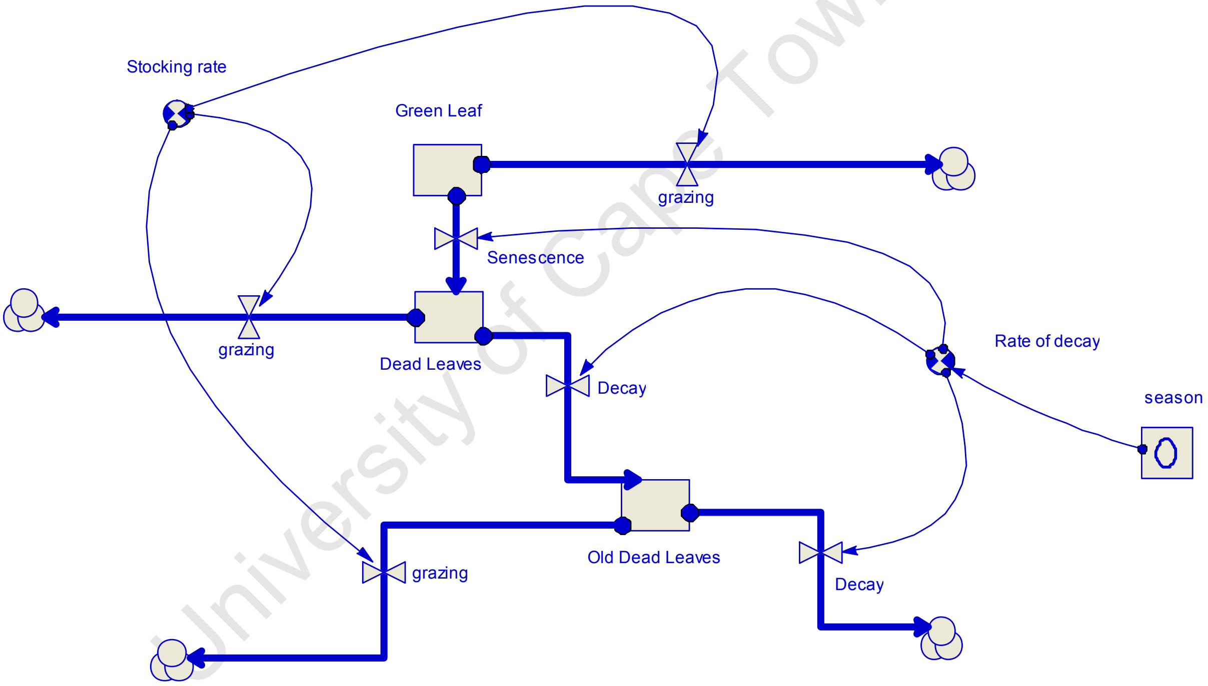

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FIGURE 3.5: Production of dead leaves and old dead leaves and the influence of grazing and decay processes. The square boxes represent quantities of respective grass structures followed by the notches representing major influencing processes.

The rate of accumulation of dead leaves, decay, and its consumption by steers computed as follows:

$$\frac{dG_{dl}}{dt} = \begin{cases} \Omega G_{gl} \quad - \quad \left(Dec_{fr} G_{dl,} + \dfrac{Dmi.G_{dl}\rho_{dl} S}{\sum \rho_i G_i} \right), & grazed\ paddock \\ \\ \Omega G_{gl} \quad - \quad Dec_{fr} G_{dl,} & resting\ paddock \end{cases} \tag{3.21}$$

Where

G_{dl} = Ω $G_{gl,}$ the rate of senescence of green leaves

Ω : is a variable parameter of the rate at which green leaves die to produce dead leaves and it depends on available soil moisture (Sm).

$\Omega = (10.57 - 0.087\ S_m)\ \varphi$; $G_{shoot} < 110$

$\Omega = \varphi$; Otherwise

φ : is also a variable parameter which depends on the amount of available shoots and growing period calculated as follows:

$\varphi = 0$; $G_{shoot} < 20$

$\varphi = 1.71x10^{-3}$ Otherwise

$\varphi = 1.71x10^{-3}$ $g_{wks} < 18$

$\varphi = \dfrac{-2.86x10^{-4}}{1 - 1.1x10^{-4}\, g_{wks}}$ Otherwise

Where

g_{wks} : growing weeks

Old Dead Leaves

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$$\frac{dG_{oddl}}{dt} = \begin{cases} Dec_{fr} G_{oddl,} + \dfrac{Dmi.G_{oddl}\rho_{oddl}S}{\sum \rho_i G_i} & grazed\ paddock \\ \\ Dec_{fr} G_{oddl,} & resting\ paddock \end{cases} \qquad 3.22$$

Inflorescence

$$\frac{dG_{\inf}}{dt} = \begin{cases} \lambda_{\inf} \dfrac{\left[1 - \left(\dfrac{G_{\inf}}{G_{i\,nf,\max}}\right)^{\theta_{\inf}}\right]}{1 + \dfrac{G_{\inf,Ksu}}{G_{su}}} - Dec_{fr} G_{\inf} - \dfrac{Dmi.G_{\inf}\rho_{\inf}S}{\sum \rho_i G_i}, & 3.23 \\ grazed\ \ paddock & \\ \\ \lambda_{\inf} \dfrac{\left[1 - \left(\dfrac{G_{\inf}}{Gi_{nf,\max}}\right)^{\theta_{\inf}}\right]}{1 + \dfrac{G_{\inf,Ksu}}{G_{su}}} - Dec_{fr} G_{\inf}, \quad resting\ \ paddock & \end{cases}$$

Dead Inflorescence

$$\frac{dG_{d\inf}}{dt} = \begin{cases} -Dec_{fr} G_{d\inf} - \dfrac{Dmi.G_{d\inf}\rho_{\inf}S}{\sum \rho_i G_i}, & grazed\ paddock \\ \\ -Dec_{fr} G_{d\inf}, & resting\ paddock \end{cases} \qquad 3.24$$

3.6 Diet Selection and Food Intake Module

Weight (*W*) is related to the energy intake (E) and energy loss through locomotion and other activities. The rate of change in individual animal weight over time as it grazes within a paddock is described by first order differential equation of the form:

$$\frac{dW}{dt} = \frac{\left(dE/dt\right)}{E_{cg}} \qquad 3.25$$

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$$\frac{dE}{dt} \quad = \quad H_b\left[B_E\left\{1-\exp(-p_E\frac{G_E}{H_b})\right\}-1\right]-En_{walk} \qquad 3.26$$

En_{walk} predicts the daily energy expenditure in walking calculated as follows:

$$En_{walk} \quad = \quad \Phi_{walk} D_{walk} \; W$$

Where

D_{walk} : Total distance an individual steer covers walking for a day

Φ_{walk} : A parameter for energy expenditure for a unit distance

H_b : denotes basal metabolism rate which measures the result of chemical change that occurs in the cells of an animal in the fasting and resting state. To compare rates at which different animals use energy, scientists calculate for each the rate at which a resting animal under no stress consumes oxygen. That consumption is then used to calculate the basal metabolic rate, which is expressed as the number of kilocalories of energy used per kilogram of body weight, per day.

$H_b \quad = \quad f_m W^{0.67}$: f_m is a parameter describing fasting metabolism.

B_E : denotes energy balance coefficient attained when the animal body energy stores remain constant. Its energy intake (metabolizable energy of food) then equals the energy expenditure (total heat output).

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Gross energy intake G_E is estimated from the animal dry matter intake (dmi) in a paddock on a daily basis as follows:

$G_E = 18.4\, Dmi$

Daily dry matter intake (*Dmi*) is limited by available forage, mouth size (arcade), and digestibility. Therefore *Dmi* is a variable parameter computed as follows:

$$Dmi \quad = \quad \begin{cases} Fe_{dmi} & Fe_{dmi} < Bi_{dmi} \\ Bid_{mi} & otherwise \end{cases}$$

Where

Fe_{dmi} : computes the dry matter intake as limited by forage biomass whereas Bi_{dmi} denotes the same when digestibility is considered the limiting factor. The two variables are further defined as follows:

$$Fe_{dmi} = Emp_{int}$$

$$\text{Emp}_{\text{int}} = \frac{Y_{\text{int}} F_{dmat}}{1 - \frac{Q_{diet}}{0.82}}$$

Where

$$Y_{\text{int}} = W_x Q_{diet} + (1 - Q_{diet}) W_x^{2},$$ calculates faecal output

$Q_{diet} = \dfrac{Me_{diet}}{18.4}$: A parameter for fecal output for animals whose weight is more than $0.2W_x$, and W_x is the weight of a mature animal measured in kg.

$$Me_{diet} = \frac{\xi_i G_i \rho_{G_i}}{\sum \rho_i G_i}$$

ξ_i : A parameter value for fractional metabolisable energy obtained from each grass structure G_i. However, the calculation of metabolisable energy from dead leaves is done as follows

$$\xi_{ddl} = \begin{cases} \xi_{Codl} & gr_{dys} = 0 \\ \xi_{Aodl} & g_{dys} < 30 \\ \xi_{Aodl} - \xi_{Codl} (g_{dys} - 30) & otherwise \end{cases}$$

The maximum rate (Bi_{dmi}) at which cows graze depends on the maximum amount of dry matter taken in one bite ($Bite_{max}$) but limited by the breadth of the dental arcade (*Arcade*) and the maximum number of bites per day ($Bite_b$). The arcade breadth is related to peak live-weight and mature live-weight. Peak live weight is the highest weight attained by the animal and is the variable used as arcade breadth does not decrease if the animal looses weight. Given this relationship the computation of the rate of intake of DM by cows is calculated as

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$$Bi_{dmi} \quad = \quad Bite_{\max} * Bite_{b} * Arcade * Adjdm$$

Where

$$Arcade \quad = \quad 8.25W^{0.29}\, W_{\max}{}^{0.07}$$

If $Arcade_{old}$ > Arcade, $Arcade_{old} = Arcade$; replacing old with new arcade

The actual rate of eating, which is the maximum rate adjusted according to shoot biomass (Adjdm), is computed as:

$$Adj_{dm} = \frac{\left(\dfrac{G_{shoot}}{G_{kshoot}}\right)^{Q_{dm}}}{1+\left(\dfrac{G_{shoot}}{G_{kshoot}}\right)^{Q_{dm}}}$$

G_{kshoot} : Parameter of intake adjustment

$$P \quad = \quad E_{gm} \ln\left(\frac{E_{gm}}{E_{gg}}\right)$$

$$E_{gm} \quad = \quad 0.503Q_{dmi} + 0.35Q_{dmi}{}^{2}$$

$$E_{gg} \quad = \quad 0.006\,Q_{dmi} + 0.78\,Q_{dmi}{}^{2}$$

Estimating the daily energy content of gain (E_{cg}), the computation is as follows:

$$E_{cg} = 23.6\,P_{cg} + 39.3\,F_{cg}$$

Where

P_{cg} : protein content of gain which can be estimated by two different methods as follows

$$P_{cg} = a_{p}W^{b_{p}}$$

$$P_{cg} \quad = \quad \frac{Q_{p}P_{\max}}{W_{\max}} + 2(1-Q_{p})\frac{P_{\max}W}{W_{\max}{}^{2}}$$

F_{cg} : Fat content of gain estimated as follows

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$$F_{cg} = \frac{Q_F F_{\max}}{W_{\max}} + 2(1 - Q_F)\frac{F_{\max} W}{W_{\max}{}^2}$$

3.7 Summary

The Richardson Savannah model has been adapted to enable simulation of the multi-paddock grazing systems in order to evaluate rotational grazing systems. The model constitutes three basic modules of water balance, plant growth and animal diet selection and food intake with responses in animal weight. The subsequent task involved coding the model into *matlab* computer language and evaluation of the model behaviour. The results are presented in the subsequent chapter.

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Chapter 4

Model Testing and Performance Evaluation

4.1 Introduction

It is common to encounter philosophical arguments on the subject of model evaluation and related debates such as whether or not a model can be validated or invalidated (Holling, 1978; McCarl, 1984), the impossibility of doing validation (Oreskes et al. 1994), and the importance of undertaking it (Mitro, 2001). These arguments suggest that the concept of validation assumes a wide continuum of meaning, thereupon creating considerable confusions in the ecological literature. Rykiel (1996) presented a comprehensive overview of the concepts relevant to testing ecological models, and fairly recent, Sargent (2004) discussed them in general. The general consensus is that the term evaluation is preferable to validation. More importantly, the idea of evaluation is to determine whether the model is able to realistically represent the system. This is essential if the model is to be used to study the effects of different management strategies.

Nevertheless, it is almost impossible to formally validate the kind of model under study, but it is possible to test each module to see if the pattern of behaviour is reasonably acceptable. Parameter sensitivity analysis involved a series of tests in which different parameter values were adjusted to see how the change affects dynamic behaviour of driving variables. By showing how the model responds to changes in parameter values, sensitivity analysis is a useful tool in model construction as well as in model evaluation. This chapter primarily addresses the third objective of the study, which is *to test and evaluate the model by verification, calibration, and sensitivity analysis.* These terms are defined below for clarification.

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4.1.1 Concepts and Definitions

Testing and evaluation of simulation models, among other activities, involve verification, calibration, and validation (Rykiel, 1996; Mitro 2001; Sargent, 2004). Validation implies the correctness or otherwise of the model and this may be extremely difficult. On the other hand, verification means to ensure that the computer program and implementation are correct while calibration refers to the estimation and adjustment of model parameters and constants to improve the agreement between model output and a data set. Practically, calibration is part of either verification or validation. The process of validation demands a series of tests to measure the accuracy with which the model reproduces theoretical knowledge and/or field observations (Jorgensen & Bendoricchio, 2001). This process is aimed at establishing whether or not the model represents reality well enough in consideration with the objectives pursued, and therefore regarded as one of the most important processes (Grant et al., 1997; Mitro, 2001).

4.1.2 Dimensions of Validation

Operating under data constraints, three dimensions of validation recognised in the literature (e.g. Sargent, 2004; Rykiel, 1996) were performed in this exercise. They include conceptual validation, operational validation and technical evaluation.

a) *Conceptual validation* refers to providing a scientifically acceptable explanation for the cause–effect relationships represented in the model, which must agree with the model output.

b) *Operational validation* intends to demonstrate that the model output meets the performance standards required for the model purpose. If the simulated system behaviour corresponds to observed behaviour of the real system, the model is an adequate representation of the system.

c) *Data validation* is to ensure that the data used for model building and model evaluations are adequate and correct. The data for the current model are from literature (Dye, 1984; Richardson, 2000).

d) *Technical evaluation* establishes whether model responses are reasonable in the light of published information rather than simply the extent to which they track the data accurately. This is important for variables for which data are not readily available, for example, amount of forage eaten by animals. Therefore the large part of this exercise involves technical evaluation of the model.

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4.1.3 Evaluation Objectives

1) To describe the model behaviour with baseline values and its responses to changing initial conditions, rainfall and stocking rates.
2) To identify model parameters, variables, initial conditions and processes most important to the behaviour of the model and those in need of further research.
3) To validate the plant model with empirical data from literature

4.2 Material and Methods

The model program was developed and coded in *Matlab Simulink,* student Release 14, Version 7.1.0.124 (Copyright 1984-2005 by The Mathworks, Inco. U.S. See the code in Appendix A). All differential equations are integrated using the *Runge-Kutta* procedure with an integration step of 0.1 day. However, the model can be run on either a daily or weekly basis since grazing management strategies at the field scale are usually scheduled at these time scales. The simulations for this evaluation are run with a single paddock.

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4.2.1 Inputs for the Evaluation

The required model inputs are rainfall, water holding capacity of the site, initial values of structural biomass of grass components, humidity, initial value of animal weight and related parameter values. Seasonal and inter-seasonal plant growth was simulated with different historical rainfall data available for over a period of eight years (1970-1973; 1977; 1979-1983) recorded in Matopos Research Station in Zimbabwe. The model uses daily rainfall as input but the program can report cumulative rainfall in output files. The onset of the growing season is determined by the date on which water stored in the B horizon exceeds 50 mm. All the simulations in this chapter are run with the 1980 rainfall data except where the influence of annual rainfall variation is explored (see Appendix B for rainfall dataset).

4.2.2 Evaluation Techniques

There are no completely objective and accepted methods for testing and improving models (Rykiel, 1996). Two techniques widely recognized in the literature such as face validation and traces, and historical validations were employed (Rykiel, 1996; Balci & Sargent 1982a, 1982b, 1984b). These techniques are described as follows:

Face Validation and Traces: a technique within the domain of conceptual validation. This usually requires examining the flowchart or graphical model in relation to the set of model equations (Sargent, 1986). Subsequent steps involved asking experts knowledgeable about the system to verify whether the model outputs are reasonable. Richardson of the Rangeland Modelling Group[3] has been useful in providing technical know-how of the system under study.

Historical Data Validation: the literature suggests that if historical data exist (or data collected on a system specifically for building and testing a model), part of the data can be used to build the model and the remaining data are used to determine (test) whether the model behaves as the system does (Sargent, 2004). However, other literature suggests that data from the real system that are used to evaluate the model must be independent from data used to develop the model (Grant et al., 1997). Parameter estimation and model validation can be extremely difficult for ecological models, which have a large number of parameters to estimate and many sub-models to validate. This is the situation facing the current model. The use of traces is the tracking of entities through each sub-model and the overall model to determine if the logic is correct and if the necessary accuracy is maintained (Balci & Sargent 1982a, 1982b, 1984b).

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4.3 Model Baseline Behaviour

4.3.1 Prediction of Soil Water Responses

This module predicts seasonal changes in water levels depicted in three different soil horizons in response to rainfall (Figure 4.1). Initially, stored water in all the three horizons remain steady until after 50 days or so of rain storms. As expected, the water levels rise to respective maximum holding capacities of 25.5 mm, 71.5 mm and 102.5 mm, respectively. Interestingly, the water levels recede in response to dry spells and remain steady as the rain discontinues for the rest of the year.

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[3] Dr Richardson is a Research Associate in the Maths & Applied Department, University of Cape Town. He a member of the Rangeland Modelling Group

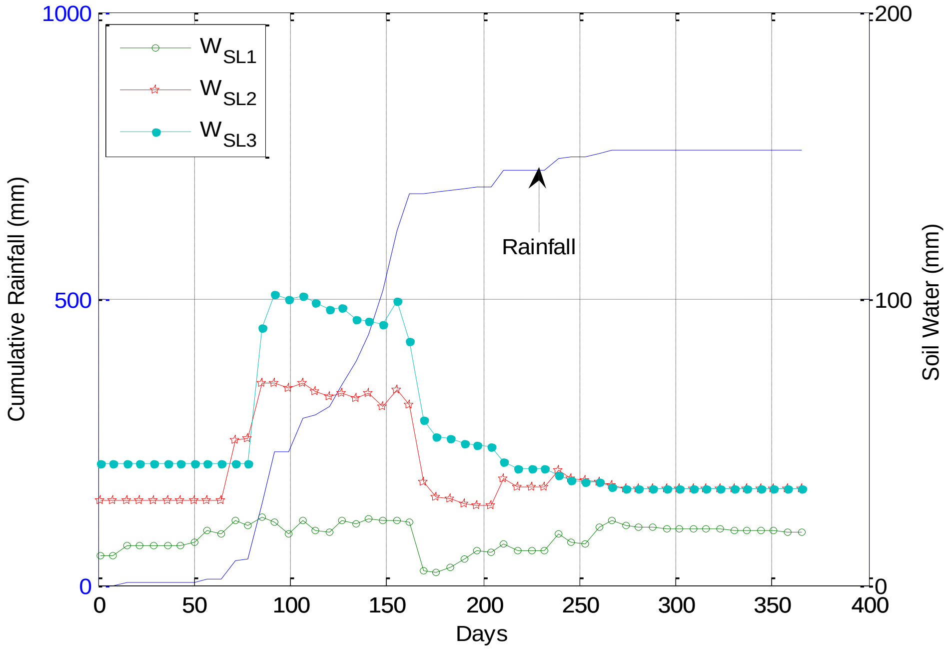

FIGURE 4.1: Prediction of seasonal soil water responses to 1980 rainfall. The model predicts changes in soil water in three different soil horizons (W_{SL1}, W_{SL2} & W_{SL3}) primarily responding to rainfall.

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4.3.2 Plant Growth

(a) Prediction of Green Leaf Responses to Rainfall

The rainfall used to run this simulation was markedly different between the years both in quantity and pattern. Green leaf biomass varies in response to variable rainfall and decay processes. The growing season begins with very low green leaf biomass, growth follows a logistic curve, cumulative rainfall limits growth period, regulates the rate of growth and limits the maximum green biomass (Figure 4.2). Plant growth initially exhibits exponential growth, but declines as rainfall culminates. With the 1980 rainfall, the green leaf biomass reaches a maximum of about 250 g m^{-2} after a period of 175 days since the first rain. Beyond this period biomass declines as rainfall culminates. Senescence and curing of green leaf produces dead leaf and therefore reduces available green leaf with time (Figure 4.2). Accordingly, the 1981 rainfall produces low biomass of green leaf. Therefore the general trend in green leaf biomass varies within and between years, primarily responding to variation in rainfall.

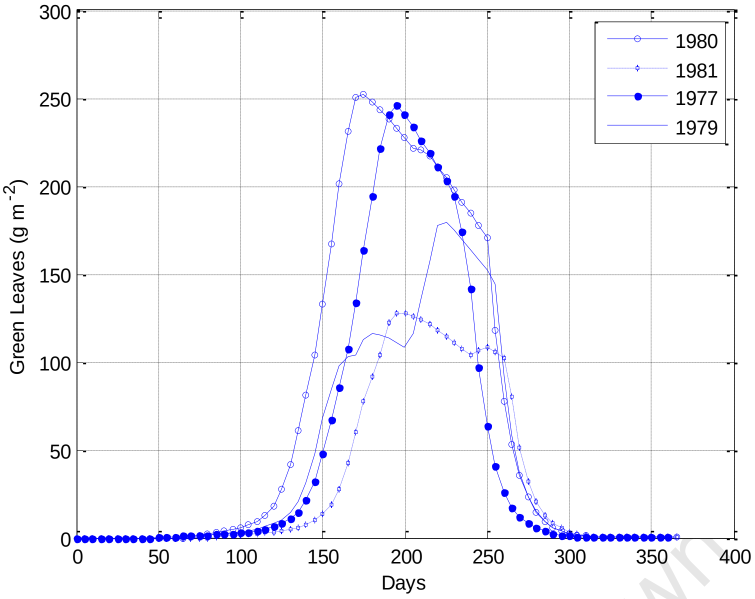

FIGURE 4.2: Prediction of green leaf biomass with different rainfall data sets for 1977, 79, 80 & 81. Biomass varies according to the annual cumulative rainfall between years and along a seasonal gradient.

(b) Shoot Biomass

The model tests show that rainfall influences shoot growth in three fundamentally different ways (Figure 4.3).

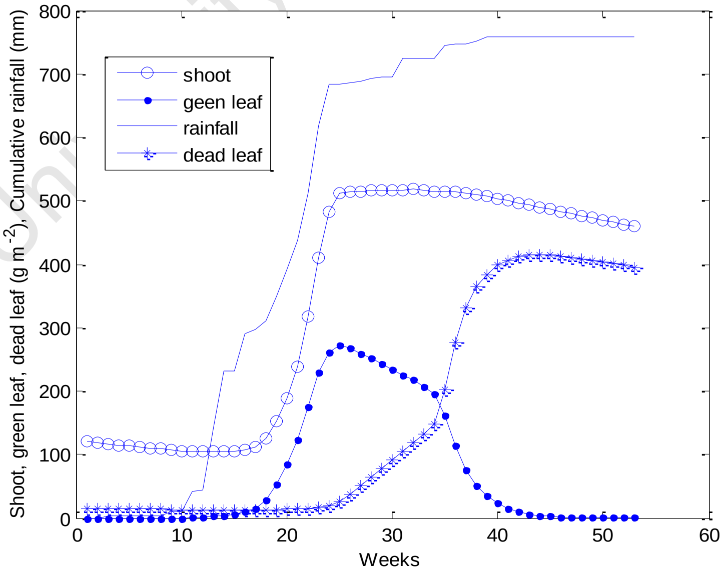

FIGURE 4.3: Model prediction on the relationship between shoot, green and dead leaf biomass and cumulative seasonal rainfall. Rainfall for 1980 was used in the simulation.

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First, green leaf biomass which forms the major input to the shoot biomass is largely influenced by cumulative rainfall. The rainfall limits the maximum biomass to the level of 369 g m $^{-2}$. Second, rainfall determines the growth period in this case the period begins from 15 weeks since it starts raining until 35th. Lastly, rainfall influences the decay process resulting in biomass of dead leaves which accumulates as part of shoot. As the growing season ends green leaf biomass declines (Figure 4.3). On the other hand, dead leaf follows a logistic growth.

(c) Culms and Inflorescences

It may be useful for the reader to appreciate the meaning of the two terms used here – culm and inflorescence. Culm is the central axis of the mature grass shoot, comprised of nodes and internodes; each node bearing a leaf. On the other hand, inflorescence is a flower head terminating the stem, consisting of a collection of flowers arranged on a common axis. These structures appear later during plant development stages. The growth of both culms and inflorescences follow logistic curves the maximum biomass being constrained by seasonality (Figure 4.4).

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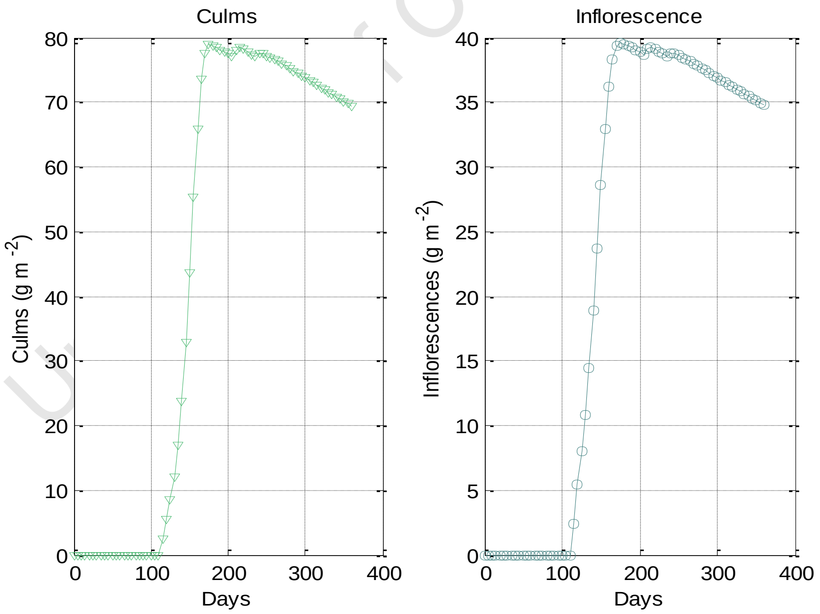

FIGURE 4.4: Model prediction of growth of grass culms and inflorescences simulated with 1980 rainfall with not grazing. The densities of both structures decline with season.

Culms and inflorescences begin to grow after 100 days since September 1. Culms grow to the maximum biomass of 80.0 g m^{-2} and inflorescences grow to 40.0 g m^{-2} (Figure 4.4).

e) Roots and Carbohydrates Reserves

Root biomass is influenced by seasonality declining as the dry season begins. Initially set at 800.00 g m $^{-2}$ the maximum biomass grows to 1360.0 g m $^{-2}$ after which the biomass reduces to 875.00 g m^{-2} due to death and decay (Figure 4.5). Carbohydrate reserves initially start with a quantity of 30.0 g m^{-2} and reach the maximum of approximately 35 g m^{-2} at the end of the year.

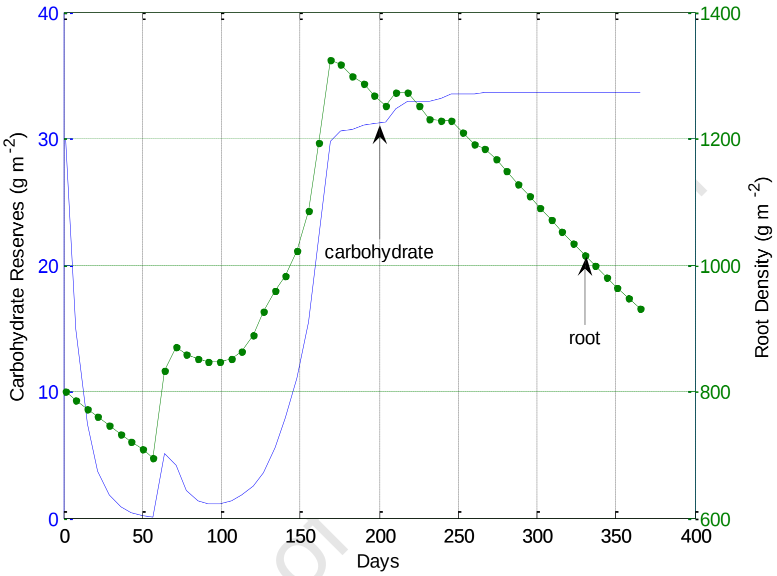

FIGURE 4.5: Prediction of seasonal root growth and carbohydrate accumulation simulated with the 1980 rainfall with no grazing. Root biomass declines with season.

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4.3.3 Model Response to Changes in Rainfall and Stocking Rate

a) Inter-annual Prediction of Shoot Growth Responses to Rainfall

Rainfall and stocking rate are the most important driving variables of the model. However, unlike rainfall stocking rate is dependent on management decisions. Inter-annual variation in biomass of grass shoot in response to rainfall was investigated by running three different simulations with rainfall data sets of four different years (1977, 1979, 1980 and 1981). The rainfall data for these years were chosen because the 1980 rainfall was relatively higher than that of 1981 and the 1977 rainfall was generally very low. Thus these datasets exhibit within year and inter-annual variability.

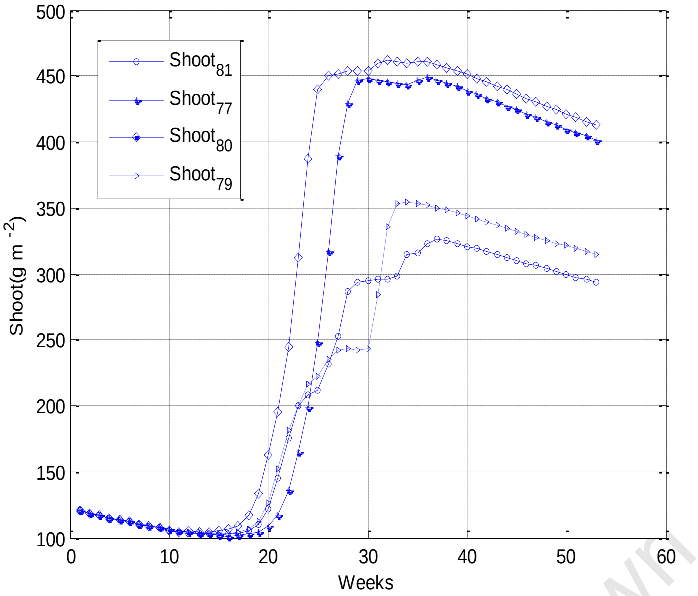

FIGURE 4.6: Shoot biomass in response to seasonally and inter-annually variable rainfall. Higher shoot peak densities and available forage at the end of the year correspond to years of high rainfall and vice versa.

b) Shoot Responses to Stacking Rate

Heavy stocking levels affect plant biomass in three different ways (Figure 4.7).

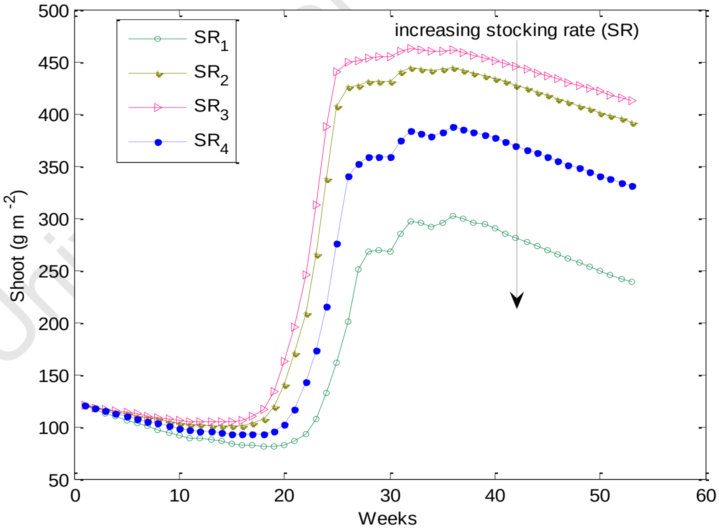

FIGURE 4.7: Shoot responses to four different stocking levels (steers ha $^{-1}$) of $SR_1 = 0.01$, $SR_2 = 0.1$, $SR_3 = 0.3$, $SR_4 = 0.6$. All simulation scenarios use the 1980 rainfall data.

First, it retards plant growth and therefore shortens the period of growth when it interacts with rainfall. Second, heavy stocking reduces availability of forage at the end of the season.

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c) Roots and Carbohydrate Reserves

Carbohydrate reserves are utilized to initiate plant growth and maintenance when photosynthetic capacity is limited, as evidenced by the reduction in reserves following defoliation (Deregibus et al., 1982). The model confirms that carbohydrate reserves respond to defoliation (Fig. 4.8).

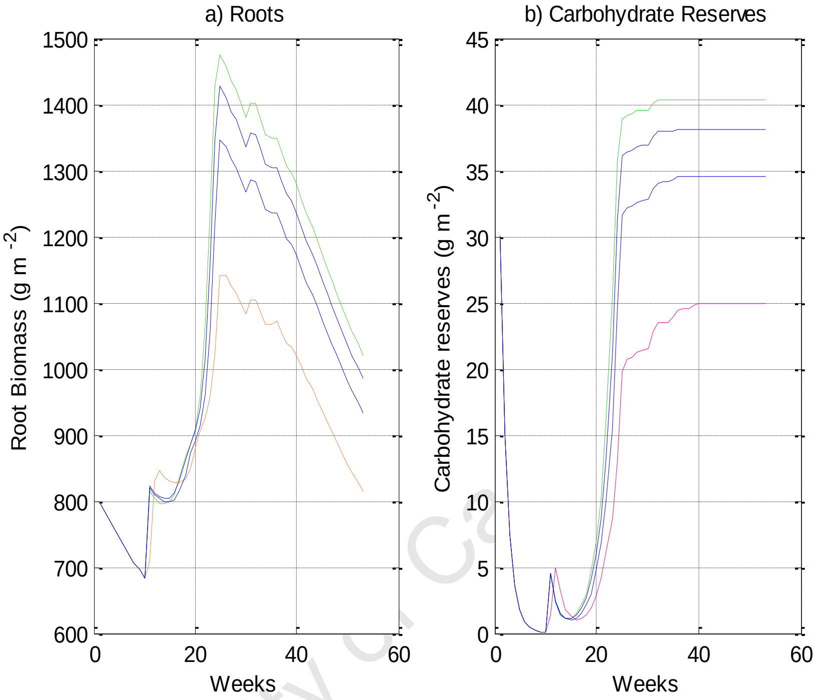

FIGURE 4.8: Root and carbohydrate responses to the effects of stocking rates on within a single growing season. Increased stocking rate reduces the amount of peak and available carbohydrate reserves at the end of year.

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In summary, the model behaviour on accumulation of carbohydrate reserves in relation to root growth is reasonable as it follows a logistic curve. The pattern of growth is generally influenced by seasonality. Various management practices such as range readiness, season of use, degree of utilization, and grazing systems are partially based upon how they affect carbohydrate reserves of grasses (National Research Council, 1962).

4.4 Model Responses to Changes in Initial Conditions

In this section the behaviour of the model as a result of changes to initial conditions is explored. We firstly consider changes to carbohydrate reserves as they are useful in initiation of growth at the beginning of the growing season. Management procedures which minimally affect the reserves would perform better than others since at the end of each growing season plenty of reserves would be available for next season growth.

4.4.1 Initial Carbohydrate Reserves and Plant Growth

The standard value of 30.0 g m^{-2} produces high shoot biomass although other values such as 80.0 g m^{-2} also produce the same biomass (Figure 4.9.1). Generally low values below 15.0 produced very low standing crop biomass. It therefore appears there is no clear relationship between shoot biomass at the end of the year and the initial carbohydrate quantities. We therefore adopt the standard value.

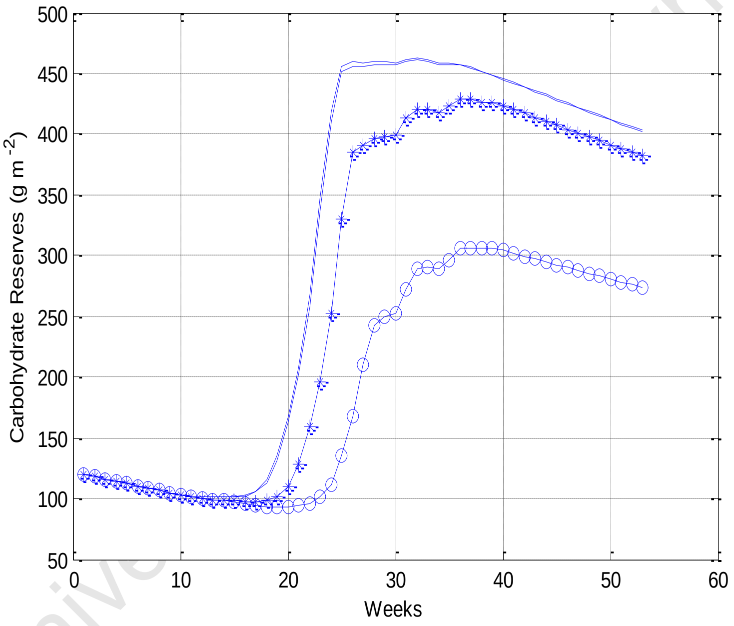

FIGURE 4.9.1: Shoot biomass responses to different initial quantities of carbohydrate reserves .The lower trajectory corresponds to 8.0 g m $^{-2}$ of carbohydrate reserves. The upper trajectories correspond to 30.0 and 80.0 g m $^{-2}$. The middle curve corresponds to 60.0 g m^{-2}.

4.4.2 Effects of Initial Shoot Biomass on Animal Weight

Available shoot biomass at the beginning of the year affects animal weight in two different ways (Figure 4.9.2). First, the loss of weight just before the beginning of plant growth depends on initial available shoot biomass. Second, initial available shoot determines the weight at the end of the season. In general, animal weight at the end of the year increases with increasing initial shoot biomass.

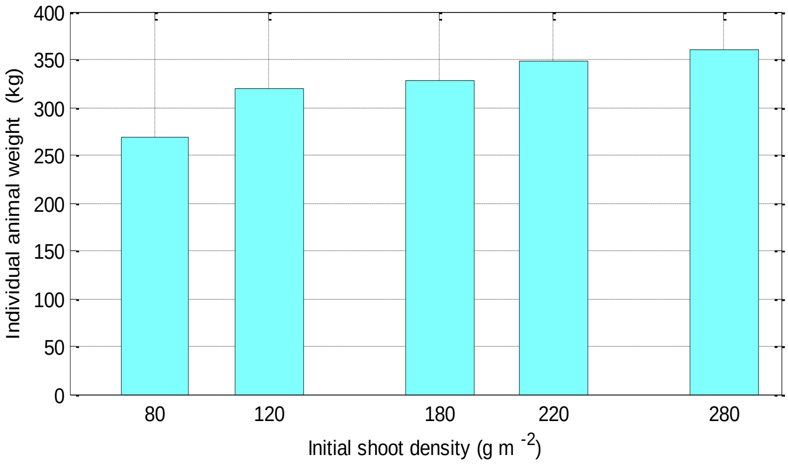

FIGURE 4.9.2: Weight gain in relation to the initial shoot biomass at the beginning of the season. Initial shoot biomass influences weight gain at the end of the season.

4.4.3 Responses to Various Stocking Rates

Initially, the animal weight is 250kg/ha but in each case of stocking rates the weight declines to the level dependent on the stocking rate (Figure 4.9.3). Animals stocked at lower rates start gaining weight earlier than those stocked at higher rates. Similarly, at the end of the growing season animals at lower stocking rates will have gained more weight than those at high stocking rates.

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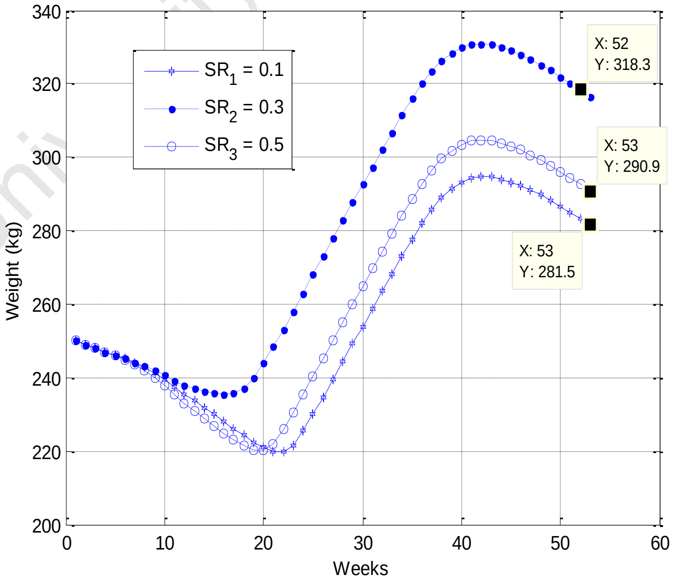

FIGURE 4.9.3: A test on prediction of animal weight at three different stocking rates, (SR) 0.10, 0.30, 0.5 steers ha $^{-1}$, respectively. Weight recorded at the end of the season decrease with increased stocking rate.

The decrease in weight in the early days of plant growth is attributable to inadequate forage to meet nutritional needs and maintenance of each individual animal.

4.5 Parameter Sensitivity Analyses

In line with Jorgensen (1994) and Brugnach (2005), the objective of the sensitivity analyses was to rank model parameters, initial values of state variables, sub-models, or even processes according to their impacts on model behaviour. A parameter that the model is sensitive to is one that minor changes in its value would result in major changes in model output or inference (Massada & Carmel, 2008). All parameters of the current model were largely from an expert with knowledge of the system under study and therefore hold a level of uncertainty. For this reason sensitivity analyses were intended to address the following questions:

1) Which parameters are important in the model output?
2) Which inputs contribute most to output variability?
3) Which parameters are most highly correlated with the output?

The model consists of a huge number of parameters adding to over 63. This makes it almost impossible to carry out sensitivity analyses scrutinizing each parameter separately. Therefore only sensitivity analysis of green leaf is carried out. Moreover, shoot growth is a simple addition of all these three structures besides old and dead leaves. But biomass of dead leaves depend on green leaves and senescence. A similar approach is employed for the sensitivity analysis of carbohydrate reserves and roots. This means, one of the analyses will be sufficient to deduce the outcome of the other as they are related. The changes to the parameters involved adjusting (increasing and decreasing) their standard values, individually by a proportion of 10 percent. In all the sensitivity analyses recorded rainfall for the 1980 was used. Because the effect changing the parameters was expected to affect animal weight at the end of the year, a stocking rate of 0.1 steers/ha was used. Initial animal weight was set at 250.0 kg.

4.5.1 The Water Balance Module

There are three modules of the water balance model with two sets of parameters (Appendix A, Table 3.1). The first set relates to parameters of water infiltration and second set represents the maximum water holding capacity. The analysis selected only

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the later. The B_{stmax} is of great interest as it involved initiating plant growth. However, results showed that changes to all parameters of the water holding capacity (A_{stmax}, B_{stmax} & C_{stmax}) affect other variables including animal weight, green leaf and root biomass (Table 4.2.1). The largest effect is on green leaf biomass as the result of increasing the Ast_{max} which eventually affects animal weight. The increase in Ast_{max} reduces the amount of water drained into the B horizon which also affects the amount of water stored in the B horizon.

TABLE 4.2.1: A summary of results on the sensitivity analysis of various variables to adjustment of parameter values of the water balance and green leaf modules by 10 percent.

Parameters	**Proportional change in variables**					
	+ 10 %	-10%	+ 10 %	-10%	+ 10 %	-10%
Water balance	**Green leaf biomass ($g\ m^{-2}$)**		**Root biomass ($g\ m^{-2}$) at end of the year**		**Animal weight (kg) at the end of the year**	
A_{stmax}	-4.50	-0.30	-1.60	-10.70	**-13.00**	-5.30
B_{stmax}	+ 5.30	-5.90	+ 4.90	-10.60	No change	-0.10
C_{stmax}	+1.60	-2.30	+ 20.30	-16.70	+ 0.20	No change
Green Leaf						
μ_{gl}	+ 8.30	-32.60	+42.20	-66.60	+1.60	**-3.40**
θ_{gl}	+ 3.80	-13.70	-10.10	-24.70	-1.20	-1.00
ks_{g}	-21.80	+7.00	-60.50	+31.30	-3.00	-0.90
$leaf_{max}$	+29.70	-43.80	-35.60	-39.90	+0.40	**-2.60**
Root						
μ_{root}	-20.20	+7.50	- 45.40	+29.10	+2.60	+1.40
$root_{max}$	- 32.00	+7.70	-88.20	+16.30	-5.10	+ 0.80
θ_{ro}	-12.60	-51.40	-28.90	-179.40	- 1.50	**-12.30**
ks_{root}	+ 47.00	-24.50	-42.60	-61.00	+ 2.00	-3.50

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4.5.2 *The Green leaf Module*

Changes to parameters of the green leaf module, all have effects on other variables. The increase in the standard value of the growth parameter, results in increased peak biomass for green leaf, root biomass and animal weight at the end of the year. This is expected since large values of the parameter increases peak leaf biomass of the green leaf produced which supports root development and the more available forage is expected for animals. On the other hand, an increase in the Michaelis-Menten constant for the green leaf substrate means that the rate of green leaf biomass is reduced following the reduction in the proportion of nutrients allocated for green leaf growth.

4.5.3 The Carbohydrate Reserve Module

Adjustments to four major parameters of the carbohydrate reserve module indicated that all have effects on green leaf root biomass and animal weight (Table 4.2.2).

TABLE 4.2.2: A summary of results on sensitivity analysis of various variables to adjustment of parameter values of the carbohydrate module by 10 percent.

Parameters	**Proportional change in variables**					
	+ 10 %	-10%	+ 10 %	-10%	+ 10 %	-10%
	Green leaf biomass (g m^{-2})		**Root biomass (g m^{-2}) at end of the year**		**Animal weight (kg) at the end of the year**	
μ_{resc}	+ 3.80	-6.30	+22.30	- 20.80	+ 1.50	- 1.50
ks_r	- 5.20	+4.00	- 17.30	+27.10	- 1.300	+ 1.70
dep_{carb}	-0.20	- 4.60	+1.50	-19.60	+ 0.20	- 1.10
fr_{carb}	+4.20	-7.10	+27.70	- 22.00	+1.80	- 1.70

However, the effect on animal weight is not substantial relative to the effects of parameters of other variables such as the green leaf and water balance modules. The carbohydrate accumulation rate parameter (μ_{resc}) positively affects other parameters when increased but the reverse is true when reduced. Similarly, increasing the fr_{carb} substantially increases the values of the variables under consideration. Increasing the Michaelis–Menten constant (ks_r) results in reduction of values of the peak green leaf, root biomass and animal weight. The reduction in animal weight is a response to reduced peak biomass of the green leaf and perhaps other variables which have not been considered in this analysis but have linkage to carbohydrate reserves. It is reasonable to

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observe a decrease in peak leaf biomass as consequence of increasing the ks_r since its increase results in decrease of the accumulation of carbohydrate reserves.

4.5.4 *Diet Selection and Food Intake Module*

The diet selection and food intake module constitutes a total of 28 parameters but we subject few to the sensitivity analyses (Table 4.2.3).

TABLE 4.2.3: A summary of results on the sensitivity analysis of various variables to adjustment of parameter values of the diet selection and food intake module by 10 percent. The values indicate the differences between the runs with standard value and the runs adjusted parameter.

Parameters	**Proportional change in variables**					
	+ 10 %	-10%	+ 10 %	-10%	+ 10 %	-10%
Diet selection & food intake	**Green leaf biomass $(g\ m^{-2})$**		**Root biomass $(g\ m^{-2})$ at end of the year**		**Animal weight (kg) at the end of the year**	
q_{dm}	-39.50	-5.00	-106.80	-0.50	-3.20	-0.10
q_{dmi}	-72.70	- 26.80	-137.60	-131.30	+ 8.90	-24.90
W_{max}	- 62.90	-66.20	-157.30	-134.50	-11.20	-5.20
fdm_{mat}	-1.70	-3.10	-6.60	-14.60	+20.70	-26.00
p_{max}	- 2.70	-18.90	-12.40	-73.70	-2.10	-2.40
Fm	-76.20	-3.30	-140.60	-15.70	-27.90	+17.10
Skakel	No effect	No effect	No effect	No effect	No effect	No effect
$bite_{max}$	-3.20	-60.90	+6.40	-125.70	+ 3.90	-13.10
k_{shoot}	- 6.10	- 3.20	-34.30	+2.80	-13.90	+7.00
$pref_{gl}$	-4.30	-2.40	-20.50	-14.90	+0.80	-0.70

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Apparently, changes to all the parameters except for the *Skakel* affect many variables of the systems although the degree of their effects differs from parameter to parameter (Table 4.2.3). The largest effects on animal weight are mostly those related to the diet selection and food intake itself and these include the Fm, fdm_{mat}, q_{dmi}, $bite_{max}$ and k_{shoot}. The Fm parameter relates to fasting metabolism. When increased by 0.1, the animal loses weight since dry matter intake reduces and utilisation of metabolisable energy for growth and fattening reduces and vice versa. On the other hand, decreasing the bite size parameter by 0.1 reduces food intake and consequently affects animal weight. More importantly, the effect on animal weight is a result of changing the fdm_{mat}, which relates to intake as limited by digestibility. When fdm_{mat} is increased, dry matter intake increases and the opposite is true. Lastly, q_{dmi} is a parameter moderating the faecal output increasing when the parameter increases and vice versa. This eventually affects the weight of the animal (Table 4.2.3).

Not surprising, both reduction and increase by 0.1 of the q_{dmi}, q_{dm} and W_{max} all negatively affect the green leaf biomass. The increase in shape parameter of bite size equation (q_{dm}) increases the intake and therefore reduces peak green leaf biomass. However, the effect in reduction by 0.1 is relatively negligible. A similar trend applies to the effect on root biomass. Increasing the maximum weight (W_{max}) reduces available peak biomass of green leaf since diet requirement also increases. However, it is surprising that reducing the same parameter by the same amount increases the reduction in the peak biomass of the green leaf.

4.6 Comparison with Published Data

Following the conceptual background to this chapter, the validation approach used here does not necessarily track the exact data of the system. To validate all the modules such as the one on food intake and selection, by way of field trials would not only be difficult but also take many years beyond the study period. The alternative method is therefore, to make comparison of some aspects of pattern of model prediction with published information (data).

4.6.1 The Water Balance Module

This module importantly demonstrates well the relationship between soil water dynamics and rainfall variation (Knoop & Walker, 1985). Soil water changes as a function of shoot biomass, transpiration and evaporation. However, these factors are incorporated in the model structure but the output is difficult to compare with empirical data. What is interesting is that the maximum levels of each respective horizon are reached before draining into the subsequent soil horizon (Figure 4.1). This module behaves close to Knoop & Walker’s (1985) empirical work.

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4.6.2 The Plant Growth Module

The model predicts the peak biomass of green leaf within the range of 120.0 and 250.0 g m $^{-2}$ depending on the annual cumulative rainfall (Figure 4.2). Similarly, the highest shoot biomass was recorded for the 1980 rainfall the maximum peak being at the value of 390.5 g m $^{-2}$(Figure 4.3). These figures fairly agree well with those of the empirical study by Dye (1984). According to Dye (1984) observed data for the 1980 rainfall, the peak green leaf biomass was as high as 245.0 g m^{-2} and the lowest was 125.0 g m^{-2} for the 1980 rainfall. Nevertheless, the current model is run starting from September 1 runs for a period of a single season of 365 days whereas the data by Dye (1984) begin from almost the same date and goes up 37 weeks only. Most importantly however, both display a logistic growth and responding to seasonal effects of rainfall.

4.6.3 Food Intake and Animal Gain

The model predicts animal gain in weight at the end of the year within the range of 250.0 to 320.0 kg depending on stocking rate, rainfall and initial weight. The initial weight of 250.0 kg was chosen to allow for comparison with published data. At lower stocking rate of 0.1 steers/ha with this initial weight, at the end of the year the animal gains up to 308.0 kg. At the high stocking rate of 0.6 steers/ha animal weight at the end of the year is 245.0 kg. Comparing with published data the figures are quite close. For example, a study examined the effect of stocking rate, rainfall and their interaction on changes in botanical composition, primary production and live weight gain per animal and per hectare in a semi-arid African Savannah (O'Connor, 2000). The cattle used in the trials were weaners of a Brahman-cross type and weighed about 250 kg on introduction, attaining weights of up to 500 kg during a year. Depending on a season's rainfall, gain per animal for the low, medium and high stocking rates, respectively, ranged between 113 and 225 kg, 82 and 220 kg and 102 and 217 kg at Llanwarne, and 151 and 241 kg, 103 and 225 kg and 76 and 215 kg at Dordrecht. These figures are comparable to those of the model prediction and observed differences are perhaps attributable to differences in animal type, rainfall of that year as well as stocking rates.

4.7 Discussion and Conclusions

The most important question to discuss is whether or not the model behaviour represents dynamics of semi-arid pastures. Behind this question lies the question of

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whether or not the model is useful for the evaluation of the different grazing management procedures.

4.7.1 Model Responses to Key Driving Variables: Rainfall and Grazing

The evaluation shows that grazing and rainfall interact to influence plant growth rate and growth period and therefore available forage. The model satisfactorily responds to variation in rainfall between years and within a season as exhibited by differences in plant production. Similarly, the model showed that with different stocking available forage at the end of the year vary. The implication for the study is that in a rotational grazing system management can manipulate grazing to ensure that plant development is undisturbed. Animal movement from one paddock to another will have to be synchronized with plant development to optimize yield, and ensure re-growth potential. During the first period, growth resumes after extreme defoliation but photosynthesis is low because of the small leaf area available for solar energy capture. Throughout the second period plants grow rapidly as a result of increased surface area. Toward the end of this phase, forage growth is near its peak producing high quality forage ideal for grazing. The transition from this phase to the subsequent phase marks the beginning of reproduction and slower plant growth. Lower leaves begin to die as they are shaded out by those above.

4.7.2 Initial Conditions and Variable Responses

Initial conditions of different variables influence their own responses as well as the responses of other variables of the model. For example, different initial conditions of dead inflorescences, old dead inflorescences, dead leaves, dead culms, old dead culms and old deal leaves , altogether influence gain in animal weight at the end of the year (Figure 4.9.2). Similarly, initial carbohydrate reserves influence forage production. The implications of these model system responses is that available forage at the beginning each growing season is very important in managing the pasture. It influences the total forage (shoot) available for grazing. Management practices which can effectively ensure adequate forage at the beginning of the each season could overcome constraints in forage availability imposed by variable rainfall within and between growing seasons. This analysis suggests that rotational grazing would be more effective than a continuous system of grazing if the total accumulation of forage for paddocks surpasses forage in a continuous grazing system or vice versa.

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4.7.3 Sensitivity Analyses

The sensitivity tests indicated that some parameter changes result in more significant effects on other variables than others do. Most important, changes to parameters of the diet selection and food intake have more effects on the animal weight than changes to parameters of other variables (compare Table 4.2.1-Table 4.23). Many parameters of the diet selection and food intake module need more research and these are parameters which showed huge effects on the animal weight including: Fm, q_{dmi}, fdm_{mat} – These The Fm in particular determines the proportion of dietary energy that is required for maintenance. Changes to the values of the water balance parameters have the least effects on animal gain although it significantly affects the plant modules. This so because, changes to plant growth modules especially the green leaf module only affects the peak biomass but not so much with the end of year biomass. Nevertheless, the parameters of the water balance module will vary from site to site depending on soil characteristics and might therefore require site-specific data to estimate their values. In general, but with exceptions, parameter values of other variables, when altered individually, only have a small influence on animal weight. For example, changes to parameters of the carbohydrate reserve module significantly affect the peak biomass of the green leaf and root biomass at the end of the season. However, these effects do not substantially affect animal weight at the end of the year. This is largely because, at the end of the season green leaf declines to zero. As such, the effects on the peak green leaf biomass are only short-lived (Figure 4.2).

Validation of a model with data is indisputably important in order to ascertain credibility of the model behaviour. However data to conduct this exercise were generally scanty. A comparison of some aspects such as peak biomass of the green leaf and shoot with published data and other sources generally exhibit an approximation of the system behaviour. Similarly, the animal diet selection and food intake showed reasonable match with published data of semi-arid systems.

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Chapter 5

Simulations and Evaluation of Grazing Systems

5.1 Introduction

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The preceding chapter presented the model evaluation exercise with satisfactory results on the model's ability to simulate plant growth in response to different rainfalls and various stocking levels. The problem under investigation concerns how to design grazing management procedures to attain productivity of rangelands in the face of the influence of variable rainfall and the effects of grazing. Rotational grazing systems are partly implemented as management options dealing with this problem. The aim of this chapter is to use the model and further understand this problem; particularly, addressing the fourth objective – *Use the model to evaluate rotational grazing systems and suggest practical modifications necessary to improve grazing management.*

The unique feature of simulation approach presented here relates to a holistic analysis. It involves several ecological attributes of the pasture. It is justified on the premise that ecosystem structures and processes are highly interconnected. As such, understanding the influence of management interventions requires the systems analysis. Knowledge of each part of the system separately does not guarantee understanding of the behaviour of the system (Grant et al., 1997). The systems simulation (or analysis) is an effective way of handling the complexity generated by the interaction among the various parts. Therefore, plant growth (above and below ground biomass), animal responses and soil water changes were analyzed for evaluation of the rotational against continuous grazing management procedures in relation to inter-annual variation in rainfall, stocking rate and timing of grazing events.

The prime idea of using a model is to conduct experiments analogous to those in the field or laboratory (Grant et al., 1997). While field or laboratory experiments involve abstraction of parts of the real system to study, important real system components and processes of various period of time are manipulated in a simulation model and enables a wider range of treatments. Moreover, simulation results may be analyzed using the same qualitative, quantitative and/or statistical techniques used in field experiments. The current model is both deterministic and stochastic as rainfall is highly variable both within and between years. Independent replications of the model output may be produced using different sets of recorded or simulated rainfall data. However, in the analysis, only single season rainfall data sets are used. Therefore, graphical displays, which do not involve formal inferential statistics, are used to indicate patterns that might not otherwise emerge from numerical measures. In other words, the analyses presented here are largely qualitative.

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5.2 Objectives

The analyses comprise two major sections. One deals with a homogeneous pasture assumed to constitute one global grass species with uniform productivity across the landscape. The second assumes a heterogeneous pasture with productivity gradient created by moisture differences, soil characteristics and plant species. The chapter addresses the following specific objectives.

1. Determine the combinations of stocking rates and number of paddocks in a rotational cycle which enhance shoot yield and gain in individual animal weights and weight gain/ha.
2. Describe the effects of timing of grazing and stocking rate on plant growth responses in different paddock systems in relation to seasonal rainfall variation.
3. Compare the predicted shoot growth and gain in animal weight in a rotational grazing strategy against continuous grazing with relatively similar stocking rates and rainfall in homogeneous and heterogeneous pastures.

5.3 Plant Responses in a Homogeneous Pasture

5.3.1 Simulation Procedure

The rotational simulation involves grazing one part of the pasture for a predetermined period and a period of non-grazing during which animals graze another part. The total area of the pasture under study is ~1000 ha. All simulations are run beginning September 1 of each growing season. In a rotational grazing the size of each paddock is proportional to the number of paddocks in the cycle. The continuous grazing procedure is simulated with animals grazing the whole pasture during the entire growing season including the dormant season. The overall effects of rotational growing on forage yield is determined as the mean of effects on all paddocks in that cycle. The initial conditions of densities for all the various variables are provided in Appendix A.

5.3.2 *Experiment 1.1: Plant Responses in a Two-Paddock System*

The purpose of this experiment was to describe plant growth responses to grazing at three different stocking rates of a) 0.15, b) 0.6 and c) 0.75 steers ha $^{-1}$ in a two-paddock system. Unless specifiec, all experimens were simulated with the 1980/81 rainfall data (Appendix B). Figure 5.1 displays results of the two-paddcok (P1 & P2) system with mean shoot biomass of P1 and P2 compared with the corresponding continuous grazing scenario.

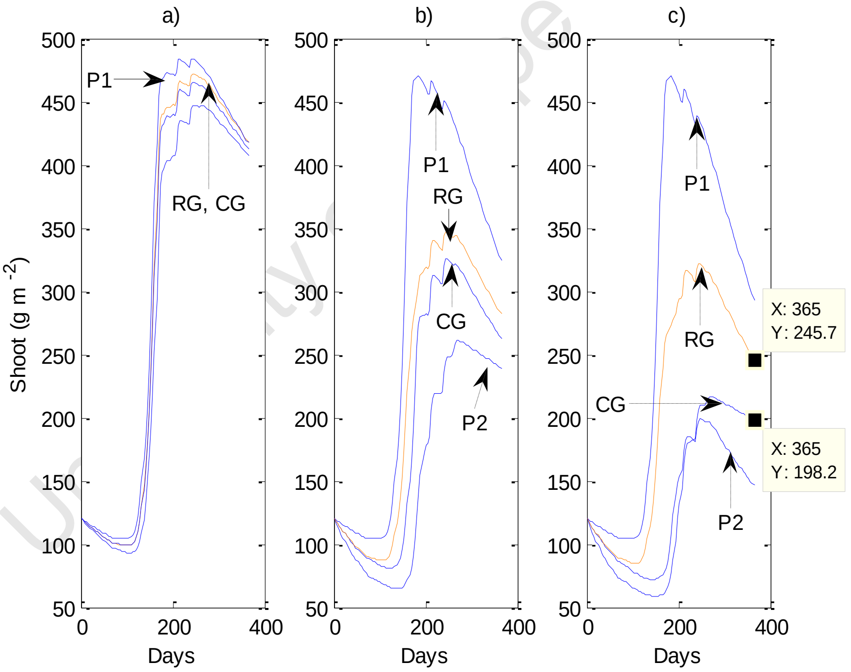

FIGURE 5.1: Prediction of shoot biomass in P1 & P2, rotational grazing (RG) and continuous grazing (CG) with stocking rates (steers/ha) of a) 0.15 b) 0.6 ha -1 & c) 0.75. Animals graze P1 during last half of the season before moved to P2. Results depend on stocking rate.

Generally, peak and end of the year shoot biomass is variable across the three stocking levels. The most important diffrences appear among paddocks and reflected further between RG and CG as follows:

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- A stocking rate of 0.15 steers ha $^{-1}$ produced no practical differences in terms of shoot biomass between paddocks, RG and CG (Figure 5.1a). The RG trajectory is only just above that of CG although peak shoot in P1 was slightly higher than P2.

- At the higher stocking rate of 0.6 steers ha $^{-1}$, shoot biomass in P1 was remarkably higher than P2 and CG. The overall effect of the two paddocks resulted in mean biomass marginally (22.1 g m^{-2}) higher in RG than CG (Figure 5.1b).
- Increasing stocking rate (Figure 5.1c) produced notable difference in shoot biomass between RG and CG. The difference is fairly substantial (47.5 g m^{-2}) representing 24 %.
- While the overall results are variable, grazing pressure (Animal ha^{-1}) for P2 is double that of CG during the first half of the season as all animals graze half the area. Similarly, grazing pressure for P1 is double during the last half of the season.

Therefore, the different results emerging from the two-paddock system within individual paddocks is attributed to differences in schedules of grazing in the rotational cycle. Similalry, the differences between the mean shoot biomass in a two-paddock system and continuous grazing are largely dependent on the interaction between timing of grazing and stocking rate.

5.3.3 Experiment 1.2: Shoot Responses to the Six-Paddock System

The purpose of this experiment was to illustrate the effects of timing of grazing and number of paddocks on plant growth in a six-paddock system and compare with results from Experiment 1.1. Table 5.1 displays the design of a six-paddock system simulated with different stocking levels (steers ha $^{-1}$) categorized as Low (0.15), Medium (0.2) and High (0.3). To allow for comparison of results this categorisation follows previous studies on the same site (Denny et al., 1977; Dye, 1984).

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TABLE 5.1: Grazing schedules for a six-paddock (P1 - P6) rotational grazing (RG). Three different stocking rates (steers ha $^{-1}$) of a) 0.15 b) 0.2 & c) 0.3 are considered. Animals graze a paddock for about 60 days before moved to the next. Results are presented in Figure 5.2.

Period of grazing schedule	**Paddock**					
	P1	**P2**	**P3**	**P4**	**P5**	**P6**
Sept 1 – Oct 31	Rest	Rest	Rest	Rest	Rest	Graze
Nov 1 - Dec 31	Rest	Rest	Rest	Rest	Graze	Rest
Jan 1 - Feb 28	Rest	Rest	Rest	Graze	Rest	Rest
March 1 – Apr 30	Rest	Rest	Graze	Rest	Rest	Rest
May 1 – June 30	Rest	Graze	Rest	Rest	Rest	Rest
July 1 – August 31	Graze	Rest	Rest	Rest	Rest	Rest

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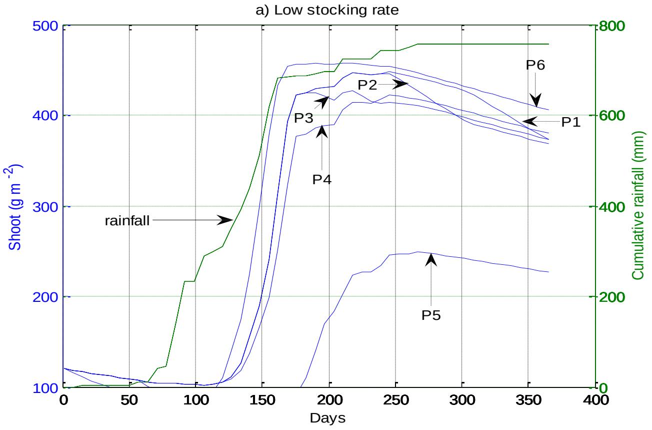
a) The Effects of Timing of Grazing on plant growth in a Six-Paddock System

Results show that timing of grazing determines peak shoot biomass as well as available shoot at the end of the year. The most striking responses are exhibited in P1, P2, P5 and P6 (Figure 5.2a-c).



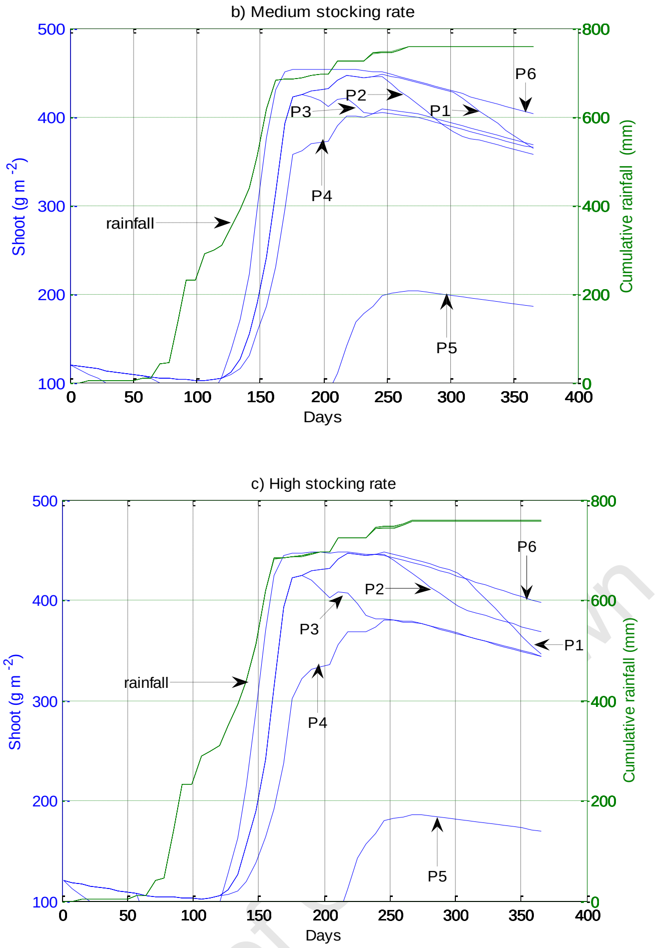


FIGURE 5.2a-c: Shoot biomass in a six-paddock system with a) Low, b) Medium & c) High stocking rates. Animals graze for about 60 days before moved to the next paddock. Timing of grazing in individual paddocks influence shoot biomass as recorded at the end of the season.

P1: Produces the highest peak forage, but at the end of the growing season yield is the same as the case with continuous grazing. This is true for all the three scenarios of stocking rates.

P2: Also produces the highest peak forage. However, at the end of the season yield is lower than the yield in P1 and CG. Relative to the P1 and P3 paddocks, there is also a sharp decline in available forage in P2 at the end of the season. This is the result of P2 grazed at the time when plant growth was still active. However, after the period of stay, growth might have concluded giving insufficient time for plant recovery. This is in contrast to P1 which was grazed at the end of the season when growth had ceased, such that plants may not have been subjected to the effects of defoliation. Similarly, P3 was grazed during part of the growth period, and after the period of stay (grazing) plants were not seriously defoliated thereby allowing for recovery during the rest of the time.

P3: The third paddock in the grazing sequence is defoliated soon after the peak of plant growth. The effects of defoliation at this stage might have been minimal.

P4: It was expected that the trajectories of P4 and P5 be adjacent to each other since they follow in the grazing sequence. However, for the reason that P5 is utilized during the period of dormancy and partly during the growth period, the effects of defoliation are less relative to those of P4.

P5: This was the most affected paddock resulting in the lowest biomass in peak forage as well as the yield of all the paddocks. This is not surprising since this paddock was grazed at the time of rapid growth at the beginning of the growing season when re-growth starts.

P6: The sixth paddock produces the highest peak forage as well as the highest yield among the paddocks and CG (Figure 5.2a, b). The explanation relates to the timing of grazing as P6 is grazed at the beginning of the dry (dormant) season. As such the effects of defoliation on plant growth is ameliorated as there is ample time for recovery.

b) Plant Responses to a Six-Paddock System and Continuous Grazing

Shoot densities vary in response to the effects of stocking rates. The highest biomass occurred under the two lower stocking rates (Figure 5.3). Shoot biomass for CG is consistently higher than shoot biomass for RG. This is striking when compared with a two-paddock system at high stocking rate which displayed contrary results (cf. Figiure 5.1c). Clearly, the increase in the number of paddocks increases grazing pressure in individual paddock as all animals have to graze one paddock before moved to the next. This is unlike the CG scenario in which grazing pressure is distributed across a lrage area throughout the season.

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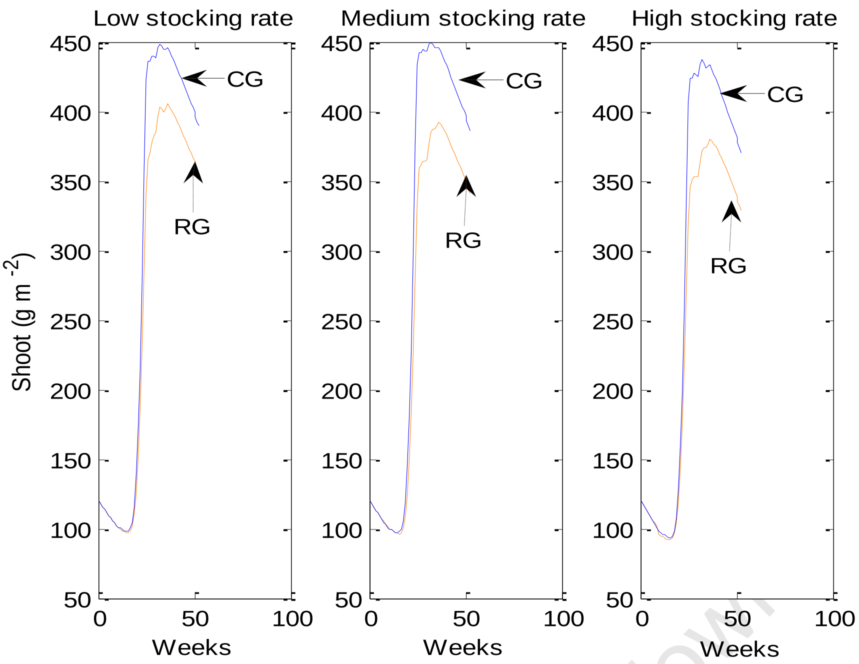

FIGURE 5.3: Shoot biomass under 1) CG and 2) RG procedures with stocking rates of a) Low b) Medium c) High stocking rates. At the end of the year, shoot biomass is consistently higher under CG than RG.

Nevertheless, this observation led to hypothesise that increasing the number of paddocks in a system reduces shoot biomass primarily due to increased grazing intensity resulting from shrinking paddock sizes. With this proposition, a follow-up simulation explored the relationship between the number of paddocks and shoot biomass (Experiment 1.3).

5.3.4 Expriment 1.3: Number of Paddocks and Shoot Biomass in a Rotational Cycle

The puprose of this run was to establish if there was any relatioship between mean shoot biomass and the number of paddocks in a cycle. The procedure followed involves simulation of shoot responses of all the paddock system in a system (number of paddocks in the cycle) and compute their mean densities at the end of the year. The pattern of shoot responses in various individual paddocks is similar to those in individual paddocks presented earlier (Figure 5.2a-c). This is true both in terms of peak shoot biomass and end of year shoot biomass.

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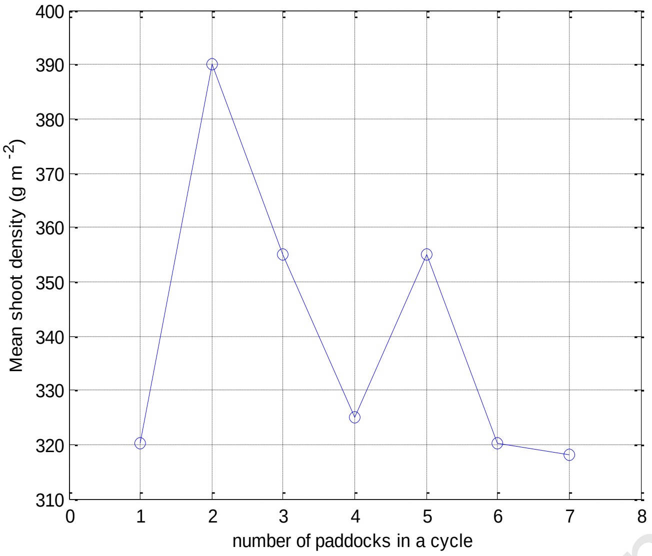

FIGURE 5.4: Prediction of mean shoot biomass with different number of paddocks in a rotational grazing cycle. One (1) paddock defines CG of whole pasture. All runs are set at the stocking rate of 0.25 steers ha $^{-1}$. Mean biomass refers to the average shoot biomass of all the paddocks in the RG cycle at the end of the year.

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○ The shoot densities recorded at the end the season range from 318.9 to 390.0 g m $^{-2}$ depending on the size of the paddock system (Figure 5.4). The over trend however, reveals a diminishing mean biomass as the number of paddocks in the rotational cycle increases from two to seven. This is consistent since by increasing the number of paddocks in the rotational cycle the sizes of individual paddocks reduce thereby increasing stocking densities with the result of increased grazing pressure.

○ Out the seven (7) runs, four (4) of them show higher biomass for RG than biomass for CG (one-paddock system), and the remaining two (2) indicate that shoot biomass for RG is equal to shoot for CG. Although the differences between one paddock system and the other are fairly small, this suggests that plant performance under RG performs better than CG especially when the number of paddocks in the system is fewer.

○ The overall shoot densities in the two-, three- and five-paddock systems were higher than densities for CG (one-paddock paddock system) and all other paddock systems. The five-paddock system emerges with surprising results contrary to the expected outcome. Following the previous trend, shoot biomass was anticipated to be lower than or closer to that of a four-paddock system. There are two possible explanations to this:

- First, with five paddocks grazing pressure is reduced since the period of stay in each paddock is less than the stay in a four-paddock system. Hence, the effects of defoliation could have been minimized. This seems only true for the comparison with the four-paddock rotation but it may not apply to the last two paddock systems (six- and seven-paddock systems). The influence of timing of grazing for individual paddocks has considerable effects (Figure 5.2a-c**).**

- Second, the most relevant explanation is that in the four-paddock scenario, animals stayed for the first period of 91 days in the first paddock. But part of this grazing period fall within the dormancy period of plant growth. The next paddock in the same system is grazed beginning exactly on the onset of the first leaf when growth is most sensitive to defoliation effects. This is unlike the case with the five-paddock scenario which involves grazing the first 73 days, all of which fall before growth initiates. This allows only one paddock to be severely affected by defoliation. Hence the five-paddock scenario yielded more than the counterparts (Figure 5.3 & Figure 5.4).

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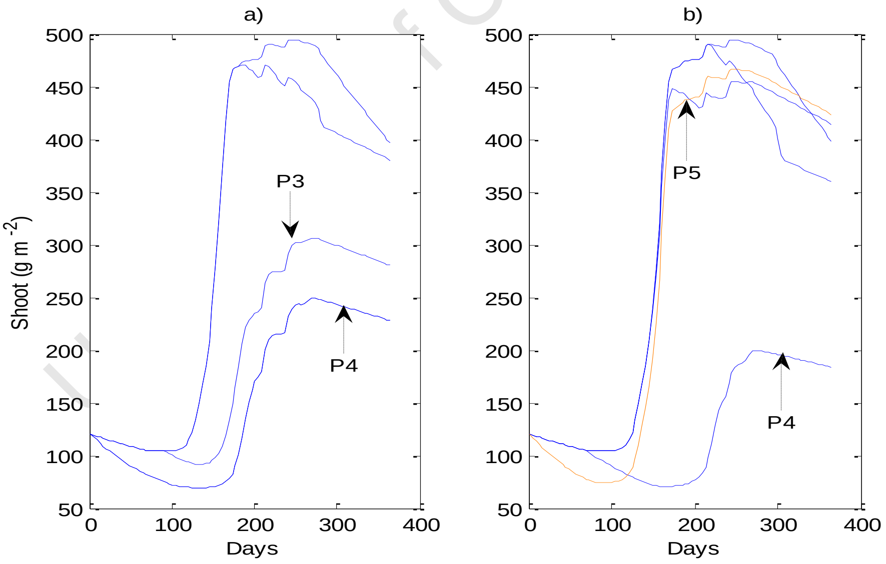

FIGURE 5.5: Prediction of shoot growth in a four-paddock system compared to a five-paddock system both stocked at 0.15 steers ha^{-1}. This figure explains why the five-paddock was higher than CG, four-paddock, six-paddock and the seven-paddock systems (Figure 5.4).

c) <u>A summary of Experiments 1.1-1.3</u>

In summary, when a strict schedule of grazing is implemented such as the one experimented here, the outcomes of plant respones in a rotational grazing is largely dependent on the proper coupling of stocking rates and number of padddcoks in the rotational cycle. Grazing of some paddocks in the rotational cycle coincides with critical period of early stages of plant development, of which the effects of defoliation are detrimental. With few paddocks in the paddock system, as stocking rate increases the differences between RG and CG are more noticeable than at the lower stocking rates (Figure 5.1a-c). The five –paddock, three-paddcok and two-paddock rotation at a stocking rate of 0.25 steers ha $^{-1}$ are a good combination as they yield shoot more than CG (Figure 5.4). To augment the observation about proper combination of number of paddocks and stocking rates, another run of the five-paddock system with a different and lower stocking rate of 0.175 ha^{-1} was simulated. Results displayed in Figure 5.5 and Experiment 1.1 support this proposition.

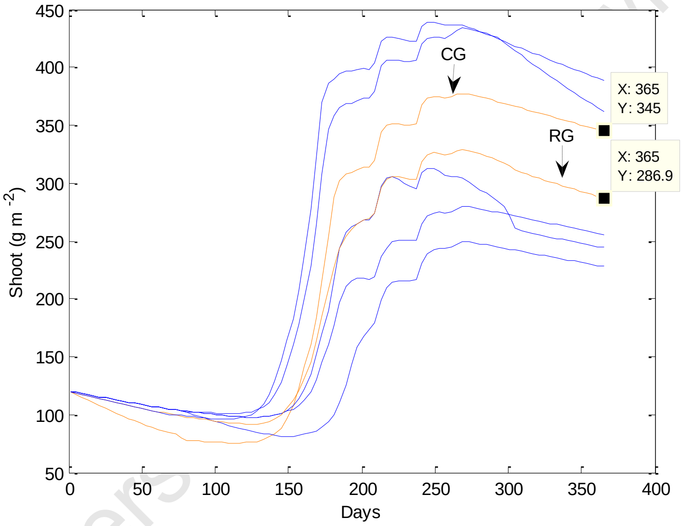

FIGURE 5.6: Prediction of shoot growth in a five-paddock system with a stocking level of 0.175 steers ha $^{-1}$. Shoot biomass is lower under RG than CG, the reverse of results of Experiment 1.3 (Figure 5.3).

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5.3.5 Experiment 1.4: The Effect of Period of Stay in a Rotational Cycle

It was inferred that the performance of a five-paddock rotation emerged better than the four-paddock rotation partly due to shorter period of stay in the former. The follow-up experiment was carried out to explore the effects of reducing the period of stay. We consider a nine-paddock system.

a) Grazing For 14 Consecutive Days

Firstly, we consider grazing a period of 14 consecutive days in each paddock. This translates into 46 days less than the period of stay in a six-paddock rotation. To avoid confounding the results, grazing is scheduled to take place during the period of most active growth. This period is assumed to begin from 1st to 73rd day and from 253rd day to 364th day of the run. Of course there is no growth within these periods. Results for the 14-day consecutive grazing scenario were in favor of CG (Figure 5.7a). However, when compared with RG the difference marginal (23 g m^{-2}).

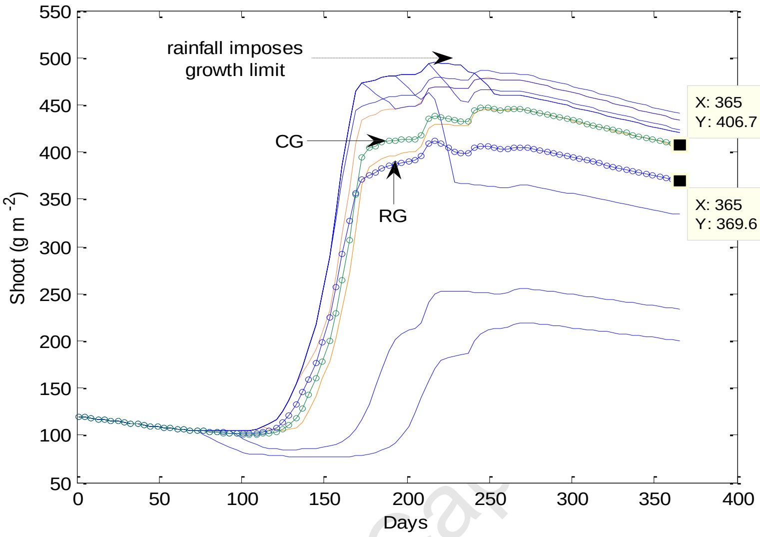

FIGURE 5.7a: Prediction of shoot growth in a nine-paddock rotational grazing stocked at 0.25 steers ha $^{-1}$. Animals graze 14 days in each paddock before moved to the next. Grazing is only confined within the period of active plant growth.

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Although shoot biomass is higher for CG than RG compared to a six- paddock system, more importantly shoot biomass in the nine-paddock was higher than the six paddock system. Specifically, the biomass in the six-paddock system was 355.8 g m^{-2} while in the nine-paddock system had 369.6 m $^{-2}$ with a marginal difference of 14.0 g m $^{-2}$.

b) Grazing For 14 Alternating Days

We now consider the second scenario where each paddock is grazed for seven (7) days during the first half of the year and seven days in the second half of the year. Reduction of the period to seven intermittent days reduces the effects of grazing (Figure 5.7b). By splitting the period of grazing into seven of stay in the first half of the season translates into the spread over time of the effects of defoliation.

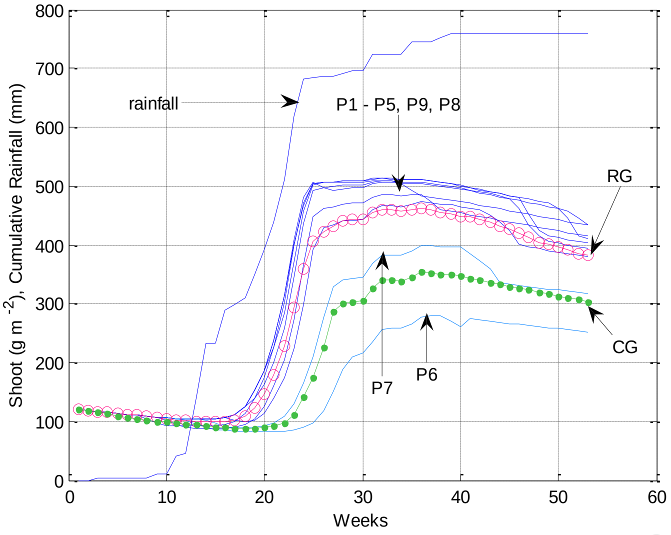

FIGURE 5.7b: Prediction of shoot biomass in a nine-paddock system; each grazing for a period of 15 days at a stocking rate of 0.25 steers/ha. Short period reduces the effect of defoliation on shoot growth in individual paddocks.

To this extent, reduction of period of stay, the number of paddocks in a rotation in combination with medium stocking rate yield better results for rotational grazing but not necessarily better than continuous grazing. A number of constraints to the performance rotational grazing in terms of plant growth as discussed elsewhere in this chapter.

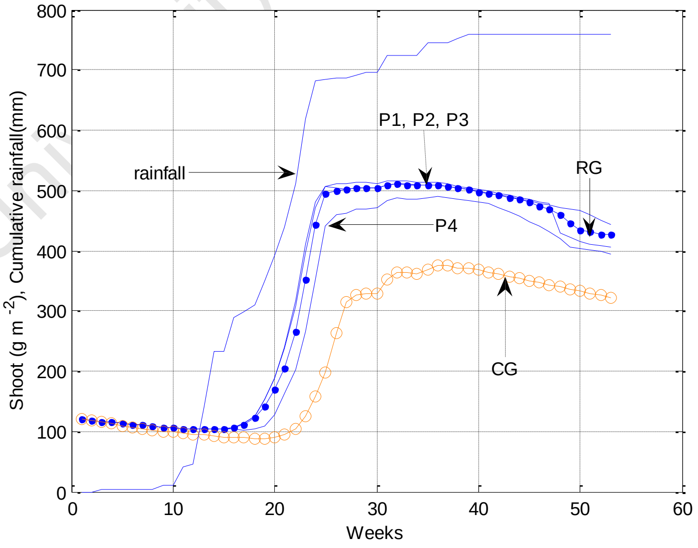

FIGURE 5.7c: Shoot biomass in a four- paddock system and four grazing periods of 15 days each and rest periods of 45 days. The paddocks are grazed 15 days during the first half of the season and 15 days during the last half at a stocking rate of 0.3 steers/ha. Fewer paddocks and intermittent grazing reduce the effects of grazing pressure compared to a nine-paddock system (Figure 5.7b).

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5.3.6 Experiment 1.5: Annual Variation in Shoot Biomass under RG and CG

The purpose of this experiment is to analyse plant responses in a three-paddock system operating between two consecutive growing seasons of 1980/81 and 1981/82 rainfall data set. Interestingly, these seasons were different in terms of the timing of rainfall as well as the total annual rainfall; the 1981/82 was relatively a dry year resulting in lower plant biomass. The three-paddock rotational grazing was simulated and compared against a continuous grazing for the same period with a comparative stocking rate of 0.5 steers ha $^{-1}$. Results revealed that, under rotational grazing, differences in defoliation effects affecting individual paddocks were more pronounced during the 1979/80 seasons but dampened down by the end of the 1980/81 season (Figure 5.8).

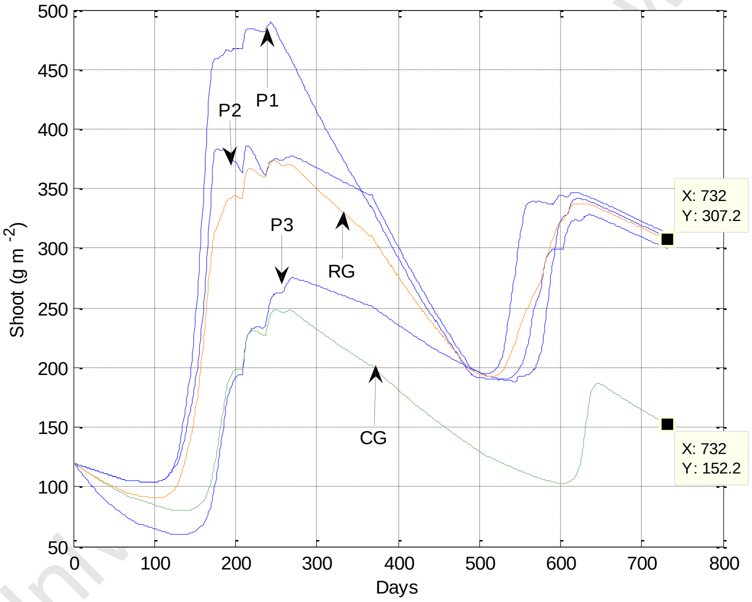

FIGURE 5.8: Prediction of plant responses in a three-paddock RG and CG operating during two consecutive years of 1979/80 and 1980/81 rainfall data sets.

The most probable reason to explain the more pronounced differences during the first season (1980/81) could be because the initial forage was much lower than forage at the beginning of the second season (1981/82). This suggested that sufficient forage available at the beginning of the season could have reduced defoliation effects in individual paddocks. As a result, overall shoot biomass was two-fold higher under RG than shoot under CG (Figure 5.8).

a) Roots and Carbohydrate Reserves

The most interesting result appears to be the timing of re-growth after defoliation from the previous year (1980/81). Re-growth under RG is initiated earlier than under CG with a time lag of about 100 days. This could be attributed to the role of carbohydrate reserves and rainfall in re-growth. Carbohydrates accumulate in roots and crowns and serve as storage organs for growth the next season. Following this observation it was hypothesized that carbohydrate reserves under RG would be higher than carbohydrate reserves under CG thereby allowing more plant growth under the former. This hypothesis was tested and results were supportive (Figure 5.9-5.10). Nevertheless, the stocking rate of 0.5 steers/ha was unrealistically high and another test was conducted with medium stocking rate but still results were the same (Figure 5.10).

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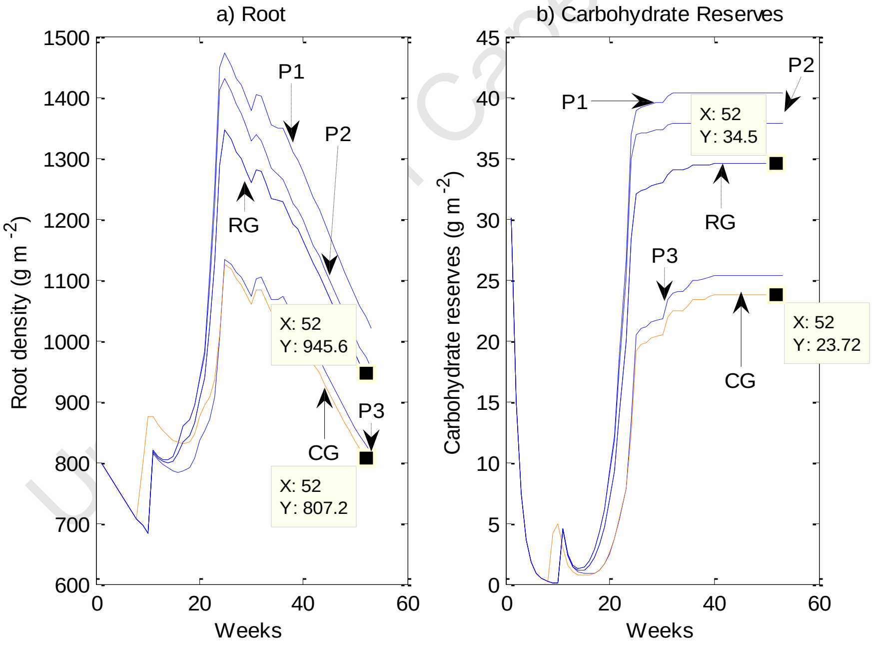

FIGURE 5.9: Prediction of a) root biomass and b) carbohydrate reserves under three-paddock RG and CG at a stocking rate of 0.5 steers/ha.

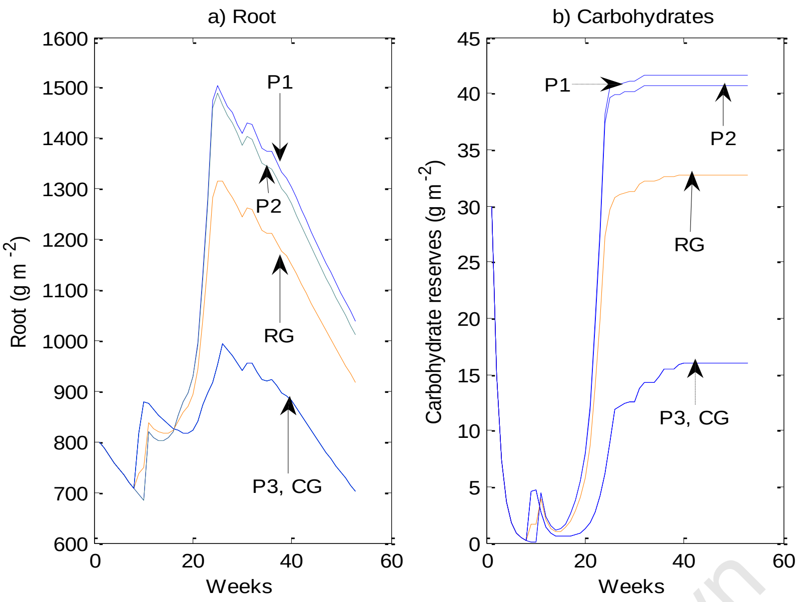

FIGURE 5.10: Prediction of a) root biomass and b) carbohydrate reserves under three-paddock RG and CG. Root biomass and carbohydrate reserves at the end of the season are higher under RG than CG. Carbohydrate reserves at the end of the season explain why there is a time lag in re-growth under CG compared to RG (Figure 5.8).

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The difference between carbohydrate reserves under rotational grazing and continuous grazing is a result of the indirect effects of defoliation on below-ground biomass. Root biomass under RG is 138.4 g m $^{-2}$ more than the biomass under CG irrespective of stocking level (Figure 5.9-10). Eventually, this difference is reflected in the initial carbohydrate reserves at the beginning of the 1981/82 season.

One more interesting result observed in inter-seasonal pattern of shoot biomass is that during the 1981/82 season; the trajectories for shoot for all the three paddocks converged (Figure 5.8). Yet, initially shoot biomass in P1 was reasonably higher than shoot in P2 and P3, and shoot in P2 was higher than shoot in P3. Two important factors might have influenced this outcome including the effects of soil water and grazing intensity.

Results emerging from these analyses on responses of root density carbohydrate reserves under RG and CG are essentially similar earlier experiments. Most important, it is evident that the combination of stocking rate and three paddocks in a rotational cycle results in higher quatntity of carbohydrate reserves and higher biomass of roots under RG than CG (Figure 5.9-10). Interestingly, the degree of effects of CG is exactly the same as those of P3 (grazing at the beginning of the season). Thererefore there is synergy between carbohydrate reserves, root, stocking rate and rainfall to determine the outcome of a rotational grazing system.

c) Soil Water and Shoot Biomass

It was hypothesized that paddocks with more shoot biomass facilitate soil water loss largely through transpiration resulting in differences in the initial soil water at the begging of the next season. This observation was followed up with a simulation of water dynamics in the second soil stratum examining the three paddocks (Figure 5.9-10). The choice of the second soil stratum and not the others is based on the understanding that initial plant growth at the beginning of the season begins when water in this stratum is above 50 mm and therefore critical for subsequent plant development.

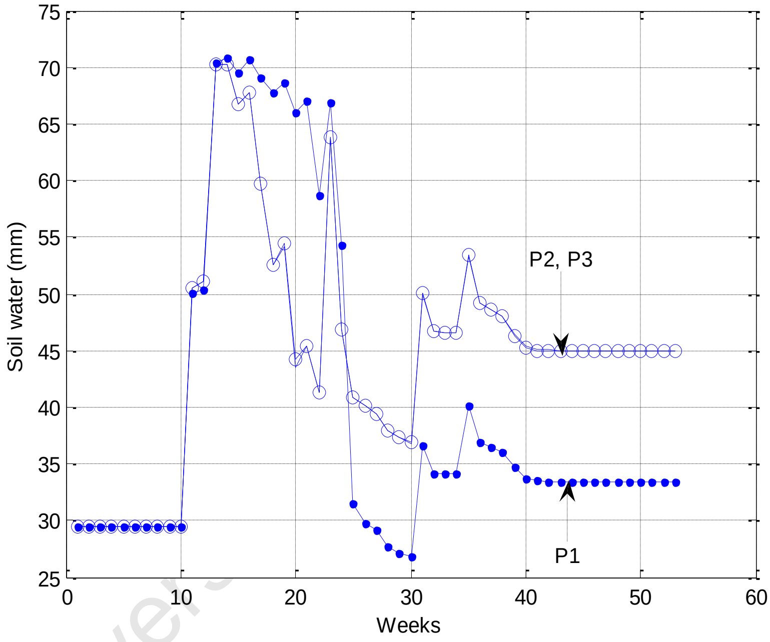

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FIGURE 5.11: Soil water levels in the second soil stratum in three different paddocks. This was simulated with the 1980/81 rainfall at the stocking rate of 0.5 steers/ha $^{-1}$.

The implication of the differences in soil water levels is that growth in P2 and P3 is initiated earlier than P1 largely because the water levels were perhaps close to the standard 50 mm (Figure 5.11). However, one would argue as to why the CG did not recover from defoliation effects since it had lower shoot than RG? The failure of CG to display similar outcomes is probably a manifestation of the overriding influence of initial carbohydrate reserves over initial soil water although this is not so simple to test.

5.4 Grazing Systems under a Heterogeneous Pasture

Experiments presented under Section 5.3 were executed under assumption that the pasture is homogeneous and that grazing selection was dominantly taking place at a plant scale. Certainly, this is plausible in some grazing environments; yet it might not be credible in areas where soils are diverse creating a mosaic of vegetation. Therefore, we now present realistic analyses presuming grazing in heterogeneous pasture with a gradient in plant productivity and patches inducing selective grazing. presumably, the process of patch-selective grazing results in the effective stocking rate on heavily used patches being much higher than that intended for the area as a whole (Teague, et al., 2003; Barnes et al., 2008). On this understanding, a grazing gradient is imposed on the range to represent high, medium and low intensity depending on distribution of grazing pressure, especially under continuous grazing. Given rotational grazing, we test the effectiveness of even distribution of the grazing pressure and make comparisons in both plant and animal responses. All the simulations use the 1980 rainfall data.

5.4.1 Representation of Grazing Gradient and Heterogeneity of the Pasture

Adjustments to the model structure are necessary to allow for simulation of a heterogeneous grazing environment. We can impose differences in soil moisture with varying productivity across the pasture with a soil moisture gradient (Figure 5.12). This can be done by simulating with different values for the parameters ASTmax and BSTmax (Appendix A). A similar pattern of pasture can be created using different growth rates and maximum potential leaf production parameters for the green leaf sub module for different zones of the pasture. The total area of 1000 ha is also considered in this analysis except that heterogeneity is imposed in the current analysis. We consider four different sizes of four zones with areas in the ratio 1:2:3:4. But the intensity of grazing still in zone is not necessarily determined by the area but rather the average number of animals preferring specific areas during the course of the year. However, it is important to note that under continuous grazing the animals select the grazing zone whereas in RG the manager decides where they graze.

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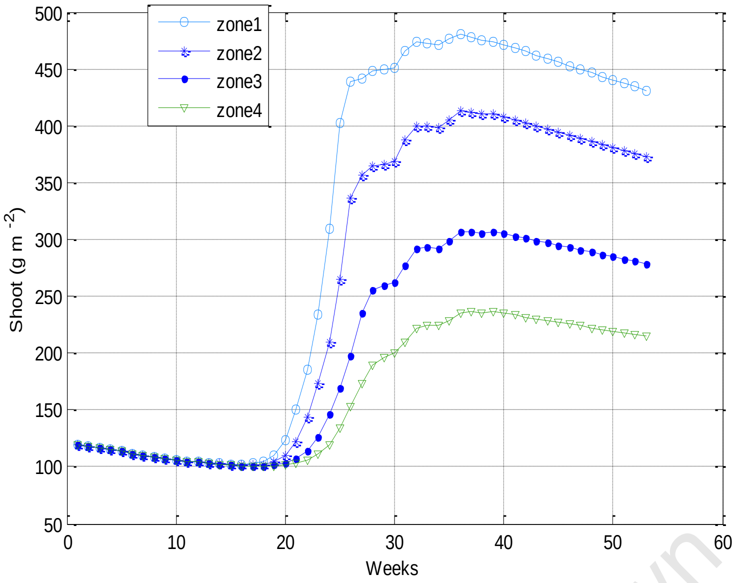

FIGURE 5.12: Plant growth responses in four different zones along a soil moisture gradient with no grazing animals. The zones are demarcated based on different forage growth rates creating a heterogeneous productivity of the pasture increasing with increasing soil moisture.

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Under continuous grazing scenario, we assume that zone 1 is closer to the water point and therefore grazing pressure increases with decreasing distance to the water point (cf. Witten et al., 2005). To capture the grazing pressure gradient, stocking rate is unevenly distributed with more animals in zones closer to the water point. Therefore, grazing selection at the spatial scale of the pasture increases with decreasing distance from the water point. Under rotational grazing, the number of paddocks in each zone varies according to the size of the zone with more paddocks in larger zones. Similarly, grazing follows the productivity gradient starting with zones of high productivity. This presumably intended to reduce the impacts of defoliation areas with slow growth rates such as zone 2 and zone 3.

Plant and animal response to a grazing procedure are determined over the whole landscape by computing the mean biomass in forage across the different zones. Similarly, gain per animal is calculated for each zone over a period of time and the overall response is determined by the mean of gain across all the zones. Similarly, to analyses in Chapter 5, we simulate different combinations of stocking rates and number of paddocks in a rotational grazing. For the continuous grazing procedure, stocking rate varies according to selection of the feeding area. Similarly, stocking rate for the rotational grazing is adjusted according to the availability of forage in the zones.

5.4.2 Experiment 2.1 – Grazing Systems in a Heterogeneous Pasture

Results of these analyses are presented for individual zones, paddocks and the overall responses of the whole pasture. The medium stocking rate of 0.25 steers/ha used in previous analyses is used here. Plant growth is generally variable across the spatial scales of measurement. However, response patterns of individual paddocks with different stocking rates were similar irrespective of stocking level. Therefore, individual paddock responses are only presented for one of the 0.25 stocking rate. Generally, variations reflect the differences in productivity of the various zones and the influence a grazing management procedure (i.e. rotational vs. continuous grazing).

(a) Plant Responses under Continuous Grazing at the stocking rate of 0.25 steers/ha

Under continuous grazing, stocking rate specific to the most productive area (zone 1) was set high at 0.5 steers/ha. Other zones were concurrently being grazed at 0.3, 0.1 and 0.1 steers/ha, respectively. On average these stocking rates give an overall stocking rate of 0.25 steers/ha for the whole pasture. At the end of the season, shoot biomass remained the highest in the most productive zone (Figure 5.13a). Thus, despite lower stocking rates, the most affected areas are those with lower productivity. The possible reason relates to low plant growth rate making recovery from defoliation effects very slow. The overall shoot biomass at the end of the season is lower than shoot biomass in zone 1.

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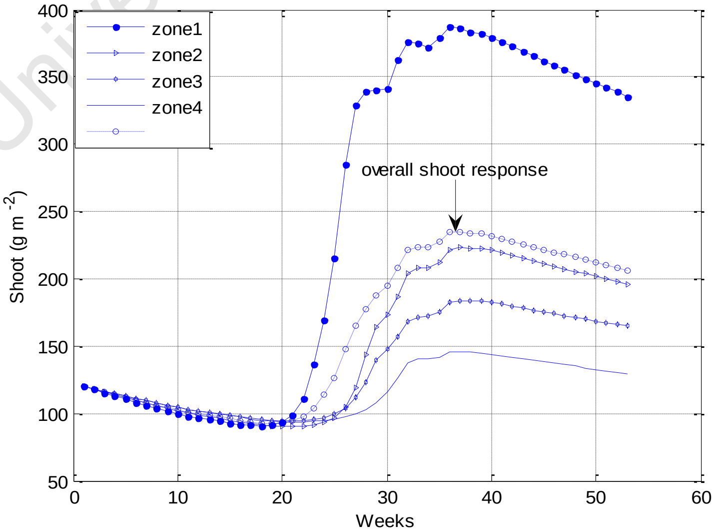

FIGURE 5.13a: Shoot responses under continuous grazing in four different zones of productivity. At the end of the season, shoot biomass remains high in the most productive zones. The overall shoot response refers to the mean of densities across the four zones.

(b) Plant Responses Under Rotational grazing at the stocking rate of 0.35 steers/ha

ZONE 1

In the first zone, four paddocks were scheduled for grazing during the first half of the season with 15 days of grazing in each paddock before returning for the second cycle of another 15 days. As expected, shoot responses are highly variable across the four paddocks (Figure 5.13b). The most influencing factor causing these variations is the timing of grazing in individual paddocks. Paddocks grazed between 10th and 15th week from the first day of the run are the most affected (paddock 2 & paddock 3). These paddocks were grazed during a critical period of plant growth. On the other hand, production in paddocks grazed during dormant period is relatively high. Grazing paddocks during critical period of early growth causes retarded growth and therefore slow recovery from the effects of defoliation (Figure 5.13b, P3).

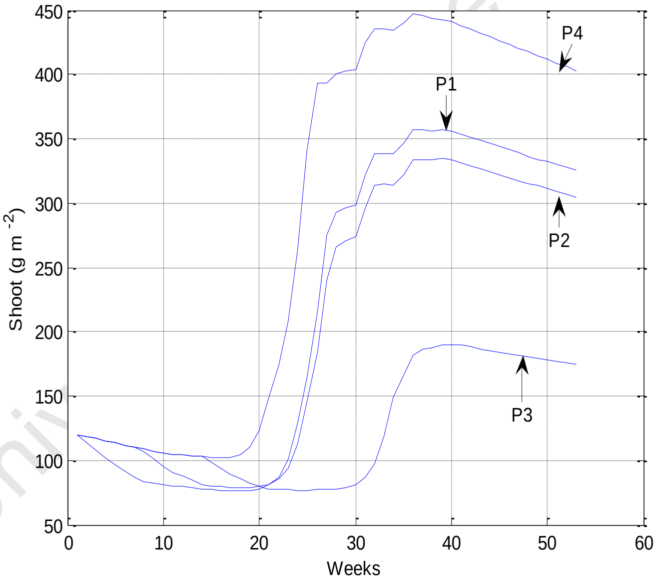

FIGURE 5.13b: Plant responses in zone 1 grazed during the first half of the season at a comparative stocking rate of 0.25 steers/ha. All paddocks are of the same size in area. Animals stay for a period of 20 days before moved to the next paddock and before returning to graze for another period of 20 days.

ZONE 2

Two paddocks were scheduled for grazing the second zone (zone 2) subsequent to zone 1. Shoot biomass in the first paddock in this zone (P5) gives the most exceptional response in two different ways. First, in the absence of grazing, the peak leaf biomass is 400.0 g m^{-2} (Figure 5.12). However, this paddock grazed under rotational grazing

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produces the maximum shoot biomass above 400.0 g m $^{-2}$ (Figure 5.14c). The increase translates approximately to 13.0 %. Second, the end of season shoot biomass of P5 is slightly higher under rotational grazing than shoot biomass in the absence of grazing (cf. Figure 5.13 & Figure 5.14c). Despite being grazed within a close period, P6 responded completely different. This is largely the result of grazing during the peak period of growth after which growth ceases thereby providing no time for recovery. All these observations identify the important role of timing of grazing in the rotational cycle. It is important when RG operates for more than two years not to graze the same area at the same stage of growth in successive years.

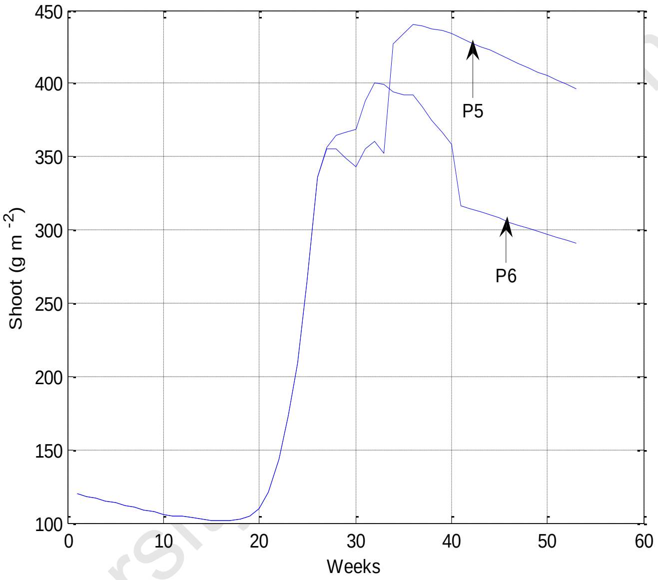

FIGURE 5.13c: Shoot responses in two different paddocks located in zone 2. Both paddocks were grazed after the 182th day of the season simulated with the same 1980 rainfall data. Each paddock is grazed two times, 15 days for each time of grazing.

ZONE 3

Paddocks in zone 3 produce equal amount of forage both in terms of end of season and peak shoot densities. The response of P7 shows that it was grazed within the period of growth giving allowance for plant recovered from the effects of defoliation. However, there was no ample time for further growth, contrary to observed results of P5 under zone 2. Unlike results on zone 2, the observed differences between the two paddocks in zone 3 may not be important. The goal in this system is to preserve as much forage as possible especially shoot biomass at the end of the season.

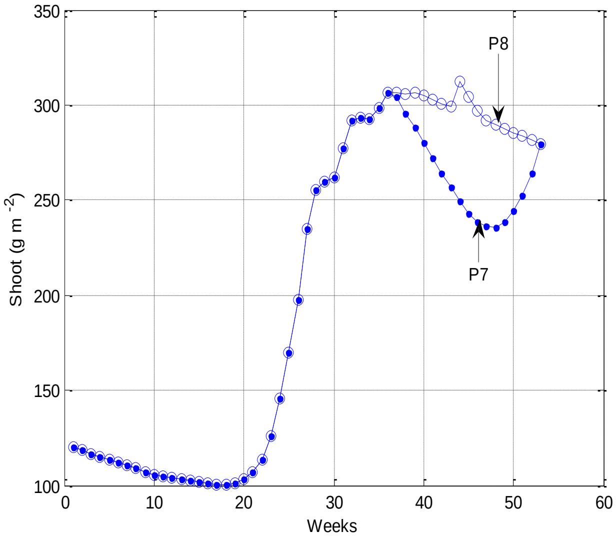

FIGURE 5.13d: Shoot responses in Zone 3 with two paddocks (P8 & P9) with the same rainfall data of 1980 at a comparative stocking rate of 0.25 steers/ha. Each paddock was grazed two times during the last half of the season, 7 days during each time.

ZONE 4

This zone is characterized by its lowest productivity among the four. In line with the rotational grazing being tested, the zone was grazed at the end of the season in attempt to reduce potential defoliation impacts and possibly preserve more forage by the end of the season. Comprising two paddocks in the grazing cycle, shoot biomass at the end of the season as well as the peak biomass did not differ (Figure 5.13e). This is largely because grazing this zone was done when active growth period had elapsed.

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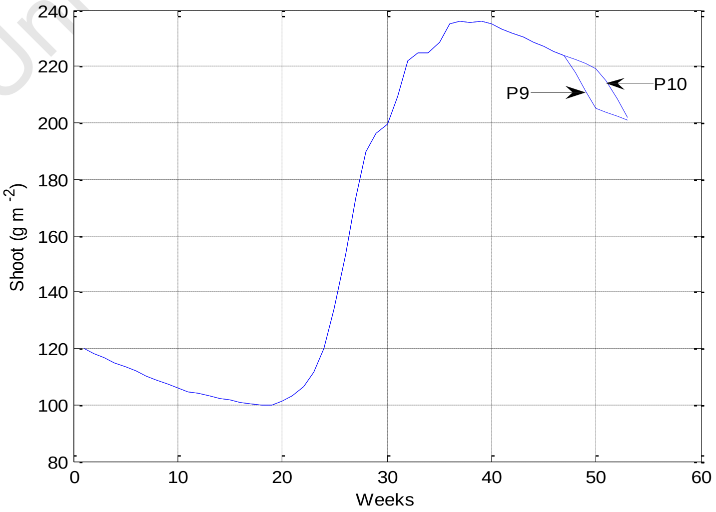

FIGURE 5.13e: Shoot responses in zone 4 with two paddocks (P9 & P10) grazed at the very end of the growing season. The simulation were run with the 1980 rainfall data at comparative stocking rate of 0.25 steers/ha.

(c) Overall Shoot Responses Under CG And RG for Each Stocking Rate

Mean shoot biomass was consistently higher under RG than shoot biomass under CG, irrespective of stocking rate (Figure 5.14f, g & h). This is true for peak as well as end of season biomass (Figure 5.14f). A reflection on results in the Section 5.3.4 particularly on the relationship between number of paddocks and shoot biomass, suggest that these results were not expected for one obvious reason. This is a ten-paddock system conducive to increased grazing pressure in individual paddocks as observed in Experiment 1.3. It was expected that this system would lead to greater or the same shoot biomass under CG than shoot biomass under RG. However, this was not observed. The overall poor plant responses under CG relative to RG were consistent for a number of important reasons. Uneven distribution of grazing pressure seriously affected plant growth in areas with low growth rates despite the light intensity of grazing in those areas. Second, grazing in individual zones was scheduled in such a way to reduce potential defoliation effects and this worked out as assumed (cf. Figure 5.14d & Figure 5.14e). Third, the system was designed for short period grazing, which allowed for quick recovery from defoliation effects. Lastly, the sequence of grazing following forage availability and plant growth further ameliorated defoliation effects (Figure 5.14e).

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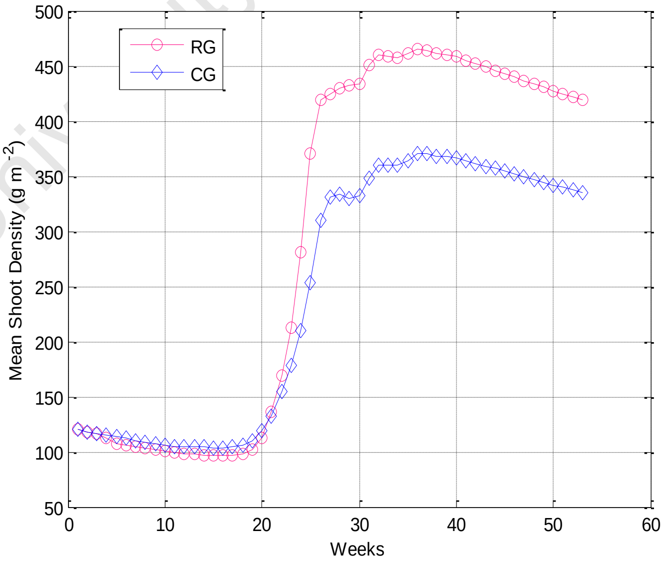

FIGURE 5.14a: Shoot responses under CG and RG with a comparative stocking rate of 0.15 steers/ha. Animals stay for 15 days before grazing again for 15 days during the third quarter of the season.

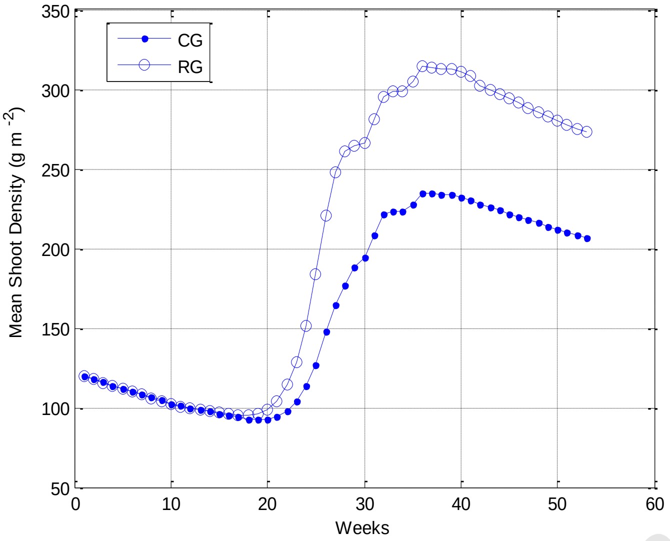

FIGURE 5.14b: The overall shoot responses to a rotational grazing under a heterogeneous pasture in contnuous grazing (CG) and rotational grazing (RG) at a comparative stocking rate of 0.25 steers/ha. The simulation is run with the 1980 rainfall data.

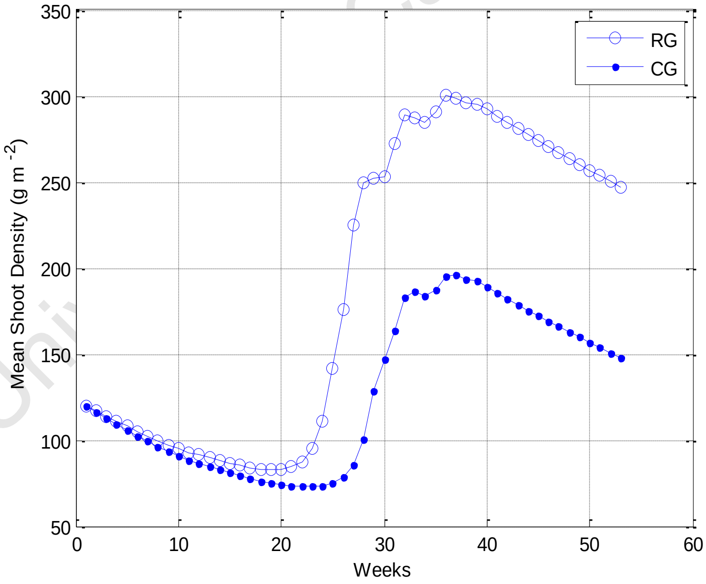

FIGURE 5.14c: Overall plant responses to CG and RG at a comparative stocking rate of 0.35 steers/ha in a heterogeneous grazing environment. The mean shoot biomass is computed for the ten paddocks with short period of grazing depending on plant growth rate and available forage.

In summary, rotational grazing under a heterogeneous pasture reduces the impacts of defoliation created by uneven distribution of grazing under continuously grazing pasture. This is possible when the grazing events under RG follow the rate of plant

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growth in various areas of the pasture. Similarly, short period of grazing and long period of resting in the rotational cycle allows for quick recovery of plants from the effects of defoliation.

5.5. Animal Performance in Grazing System

The simulation and analyses of animal responses involves an initial weight of 250 kg of individual animals at the beginning of the season in the first paddock. When animals are shifted to the next paddock in the grazing schedule, the initial weight in that paddock is the last weight recorded in the previous paddock. This process is repeated until all paddocks are grazed and the weight at the end of grazing the last paddock represents the weight at the end of the season.

Tables 5.2 – 5.4 display results for the three different stocking rates of 0.15, 0.2 and 0.3 steers ha $^{-1}$ with animals separately grazing under CG and RG management procedures. A summary of the results are further presented in subsequent figures. There are three important trends in gain in animal weight. First, animal weight changes across paddocks (Tables 5.2 – 5.4) with the same stocking rate. Second, animal weight changes between and across stocking rates in different paddocks. Trends in animal weight are analyzed parallel with average daily dry matter intake (ADMI).

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TABLE 5.2: Prediction of average daily intake and corresponding animal weight. Each paddock is grazed according to the total number of paddocks in a grazing cycle and all runs are set at a stocking rate of 0.15 steers/ha. Schedules of grazing are allocated in ascending order of paddocks (P1 – P8) beginning from P1. The initial weight for each of the first paddock in the cycle is 250.0 kg for individual animal.

No. of paddocks	ADMI (kg.day): Average daily intake during the period of stay in each paddock. W: gain in weight (kg) at the end of grazing the paddock															
	P1		**P2**		**P3**		**P4**		**P5**		**P6**		**P7**		**P8**	
	ADMI	W	ADMI	W	ADMI	W	ADMI	W	ADMI	W	ADMI	W	ADMI	W	ADMI	W
1	5.829	**326.9**														
2	4.80	253.5	**6.78**	**334.3**												
3	3.82	224.4	6.09	299.7	**6.57**	**370.8**										
4	3.87	230.5	5.35	239.7	7.41	330.6	6.11	**378.9**								
5	3.90	235.3	3.45	221.0	6.77	281.4	7.70	340.2	2.54	**333.7**						
6	4.00	238.5	3.52	221.3	6.74	254.2	8.09	314.6	6.99	379.3	5.97	**408.1**				
7	4.06	240.7	3.55	222.9	5.29	208.1	6.52	261.2	8.09	341.8	6.77	399.3	**5.86**	**422.1**		
8	4.09	242.0	3.64	225.5	3.16	206.9	6.69	242.4	7.47	306.8	7.92	372.3	6.51	428.5	5.94	**430.3**

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TABLE 5.3: Prediction of average daily intake and corresponding animal weight (kg). Each paddock is grazed according to the total number of paddocks in a grazing cycle and all runs are set at a stocking rate of 0.2 steers ha $^{-1}$. Schedules of grazing are allocated in ascending order of paddocks (P1 – P8) beginning from P1. The initial weight for each of the first paddock is 250.0 kg for individual animal.

No. of paddocks	ADMI (kg.day): Average daily intake during the period of stay in each paddock. and gain in weight (W) at the end of grazing															
	P1		**P2**		**P3**		**P4**		**P5**		**P6**		**P7**		**P8**	
	ADMI	W	ADMI	W	ADMI	W	ADMI	W	ADMI	W	ADMI	W	ADMI	W	ADMI	W
1	5.768	**315.5**														
2	4.43	233.9	6.42	**318.7**												
3	3.75	214.4	4.06	291.0	6.45	**352.5**										
4	3.64	223.1	5.06	244.4	7.26	324.4	5.96	**367.9**								
5	3.72	229.4	3.14	202.6	6.28	249.2	7.28	334.7	6.0	**382.6**						
6	3.80	233.5	3.28	209.4	6.50	242.8	7.33	302.9	6.88	372.5	5.90	**403.6**				
7	3.80	236.6	3.27	214.3	3.50	221.4	6.85	274.7	8.09	339.2	6.60	396.5	5.80	**407.4**		
8	3.73	237.9	3.26	217.7	2.80	200.4	4.77	236.3	7.09	301.3	7.86	371.0	6.19	414.3	5.68	**421.0**

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TABLE 5.4: Predictions of average daily intake and corresponding animal weight. Each paddock is grazed according to the total number of paddocks in a grazing cycle and all runs are set at a stocking rate of 0.3 steers/ha. Schedules of grazing are allocated in ascending order of paddocks (P1 – P8) beginning from P1. The initial weight per animal for each of the first paddock in the cycle is 250.0 kg.

No. of paddocks	ADMI (kg.day): Average daily intake during the period of stay in each paddock. W (kg): gain in weight at the end of each stay															
	P1		**P2**		**P3**		**P4**		**P5**		**P6**		**P7**		**P8**	
	ADMI	W	ADMI	W	ADMI	W	ADMI	W	ADMI	W	ADMI	W	ADMI	W	ADMI	W
1	**5.601**	**305.0**														
2	3.95	253.5	6.73	**311.9**												
3	3.15	207.5	3.45	283.4	5.97	**347.4**										
4	3.25	217.6	2.49	191.4	6.69	273.4	5.81	**338.8**								
5	3.36	223.9	2.76	187.5	5.54	248.0	7.24	304.1	5.76	**364.4**						
6	3.42	228.9	2.91	199.2	3.13	233.7	7.68	290.5	6.85	373.5	5.95	**423.3**				
7	3.42	232.5	2.92	204.3	3.37	179.8	5.74	225.5	7.35	313.1	6.30	389.0	5.73	**434.5**		
8	3.50	234.8	3.08	211.4	2.80	187.4	6.25	213.2	7.42	270.1	7.70	340.2	5.77	364.2	5.84	**410.1**

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a) Trends Across Stocking Rates

Independent of the category of stocking rate, the general trend shows that at the end of the season, animal weights increase with number of paddocks in a rotational cycle (Figure 5.15). However, it was interesting to note three important patterns about animal responses in a rotational cycle at different stocking rates:

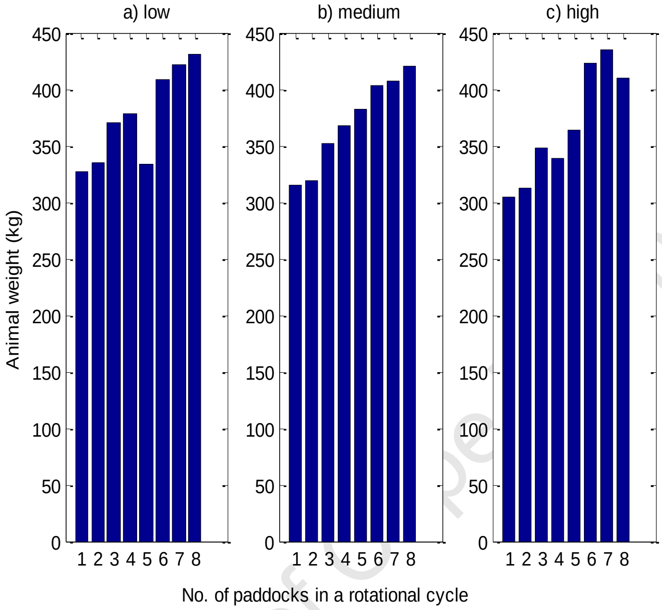

FIGURE 5.15: End of year animal weights recorded in each paddock system. The single paddock (1) represents whole pasture season-long continuous grazing. Stocking levels (steers ha -1) were respectively at low (0.1), medium (0.2) and high (0.3).

- The general trend of increasing weight for all stocking levels is attributed to the benefit of resting paddocks implicitly attributed to factors such as increased green leaf biomass and explicitly to differences in average daily dry matter intake.

- End of year highest weights of 430.3 and 434.5 kg were respectively recorded under low and high stocking rates. Fairly lower weights were recorded in a two-paddock system and CG at high stocking rates. Both of these observations relate the changes in average daily dry matter intake (Table 5.2-Table 5.4; Figure 5.16) as a resultant of differences in grazing schedules observed earlier on.

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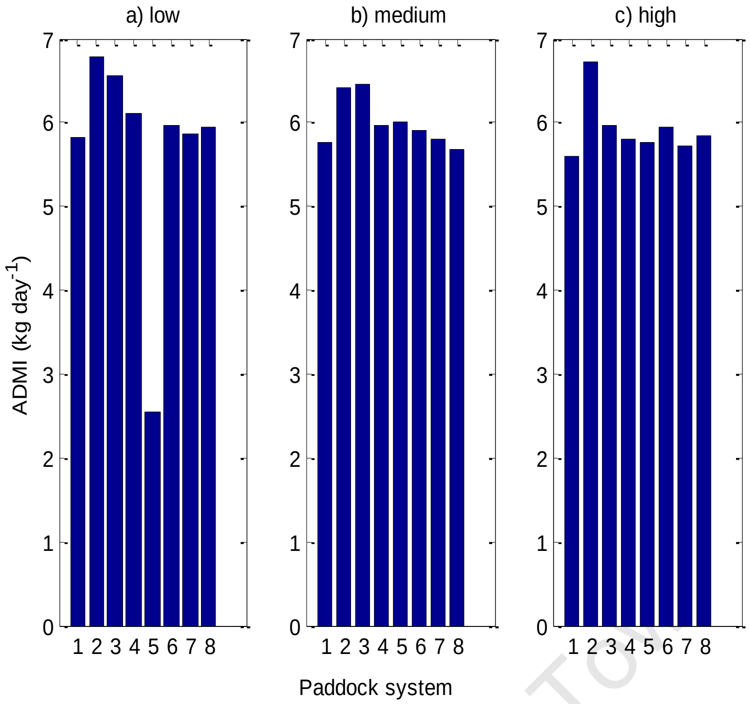

FIGURE 5.16: End of season average daily dry matter intake for each stocking level: a) Low b) Medium c) High. The figure corresponds to the data for each stocking rate from Table 5.1 – Table 5.4 in the column of ADMI for each last paddock in the cycle. ADMI refers to average daily intake during the period of stay in each paddock.

Observed variations in weights and daily dry matter intake perhaps reiterate the earlier deductions that the performance of RG depends on the proper combination of stocking levels and number of paddocks in the rotational cycle. Proper combination of stocking rate and the number of paddocks in a rotational cycle facilitates efficient harvest of forage to satisfy animal nutritional needs.

b) Trends Across Paddocks Within a Rotational Cycle

Irrespective of the stocking level or a grazing system, animals initially experience loss of weight during the first 75 days or so. However, this loss is magnified with the increasing number of paddocks in the rotational cycle (Tables 5.2 – 5.4). It is a trend attributed to the interactive influence of dry season, timing and grazing intensity. This trend is equally true for the continuous grazing procedure (Figure 5.17).

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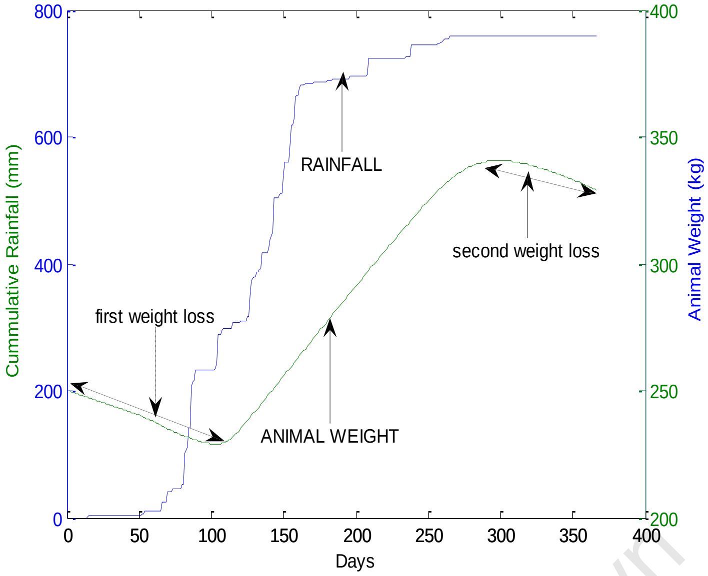

FIGURE 5.17: Illustration of the seasonal influences of rainfall on animal weight. The 1980/81 rainfall data (Appendix B) was used for the simulation. This is a run for CG at a stocking rate of 0.15 steers/ha.

Irrespective of a grazing procedure, during the first 75 days or so green material is either not available or insufficient to satisfy animal nutritional needs as this is a dry period (Figure 5.17). However, during this period rotational grazing does not have negative impacts on plant growth but daily intake declines as available forage depletes. Similarly, at the end of the season, beginning on the 25th or so days, the green material dries up and decays resulting in reduced intake of the green leaf and consequently animals encounter the second loss in weight (Figure 5.17).

Rangeland Condition with Root/Shoot Ratio

Understanding a change in the characteristics of the rangeland ecosystem is essential when making management decisions. So far, the analyses in the previous sections have analyzed the state of the rangeland by describing the above ground plant biomass and animal responses. To execute effective strategies in the case of degraded condition requires an understanding of the processes involved including water-use efficiency, root development and litter turnover, which vary depending on the degree of rangeland degradation (Snyman, 2009). Ecological interactions in arid ecosystems, such as competition and other factors that control plant distributions, primarily occur belowground (Brisson & Reynolds, 1997; Ghebrehiwot et al., 2006; Hartle et al., 2006; Palacio & Montserrat-Marti, 2007; cited by Snyman, 2009). Therefore, extrapolating

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from aboveground observations to belowground functions can be misleading (Hartle et al., 2006). However, in Chapter 1 it was argued that studies on belowground plant responses to describe rangeland condition under rotational grazing systems are generally uncommon. Two important measures can be used to describe the condition of a rangeland and these include water use efficiency (WUE) and root/shoot ratio (. Snyman, 2009). Because of the complexity involved in the computation of former, we only consider the later. Snyman found that that in a semi-arid rangeland the mean monthly root/shoot ratios for rangelands in good, moderate and poor conditions were 1.16, 1.11 and 1.37, respectively. Unfortunately, these figures are not comparable to those obtained in this analysis, particularly for the six-paddock system (Figure 5.18).

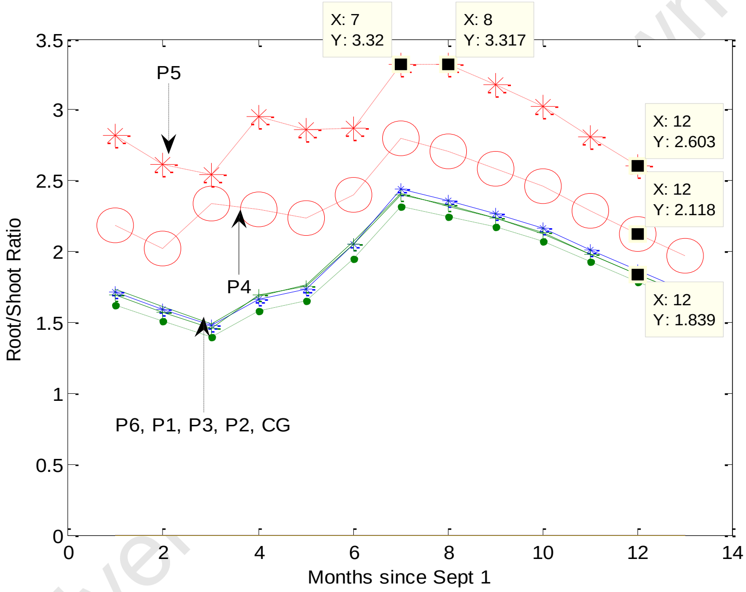

FIGURE 5.18: Monthly changes in Root/Shoot ratio in a six-paddock system with a stocking rate of 0.15 steers ha $^{-1}$.

The largest root/shoot ratios correspond to P5 in the six paddock system ranging from 2.5 to 3.35. Even the lowest ratios are far beyond those obtained by Snyman (2009). These figures suggest that there is more production of root biomass than shoot. The huge differences between the figures in this analyses and the former can be attributed to initial root and shoot densities used in the simulations. The differences in plant species, soil and rainfall between the two study sites are also applicable. It is not clear whether or not the work by Snyman involved grazing animals. If not, the removal of shoot in this study by grazing is a possible factor contributing to the huge root/shoot ratios. Otherwise, in comparison with Snyman’s classification, the whole pasture in the current study is in the state of degradation which may not be attributed to grazing or a particular grazing management procedure.

5.6 Discussion

The analyses presented in the forgoing sections produced a novel explanation suggesting that the complication in successful implementation of rotational grazing systems as management tools is a consequence of numerous and interacting factors. These factors include rainfall, a combination of stocking rate and number of paddocks, the timing of grazing schedules, and the period of grazing paddocks besides spatial and temporal variability of the pasture. More importantly, plant responses vary in time and space and therefore judging the influence of a grazing management procedure depends on the spatiotemporal scale of evaluation. The key findings suggest that rejection of the usefulness of rotational grazing systems to enhance rangeland productivity is premature as discussed below:

5.6.1 Plant Responses to Rainfall and Grazing Management

In semi-arid rangelands, a great deal of knowledge about the relationship between plant growth and rainfall at large spatial scales is well established in the literature (McNaughton, 1985; Sala et al., 1988; Ellis & Swift, 1988; Sala et al., 1988; Scholes & Walker, 1993; Bayer & Waters-Bayer, 2004). At a regional scale annual net primary production is correlated with mean annual precipitation (Lauenroth, 1979; McNaughton, 1985; Sala et al. 1988). Chapter 1 argued that much less is known about the controls of the temporal, inter-annual variation of productivity at lower spatial scales of paddock and farm.

Part of analyses in the previous sections attempted to explore the dynamic responses of savannah rangeland to grazing management and rainfall variability. Results reveal that plant growth under rotational grazing systems is influenced by the interactions between seasonality, stocking rates, timing of grazing, and the number of paddocks in a rotational cycle.

a) The Influence of Rainfall

How does rainfall influence the performance of a grazing system? Model prediction of plant growth is line with the literature. Studies have established that grass growth at the

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site scale heavily depends upon summer rainfall, as rainfall during winter is generally too low to support growth (Dye, 1984; Snyman, 2005b; Figure 5.18). Similarly, the current study indicates that cumulative rainfall influences plant growth in three different aspects that eventually affect the performance of RG. First, with no grazing animals, rainfall imposes the maximum plant production (Figures 5.1-5.4; Figure 5.19). In limiting plant growth, the negative effects of defoliation can outweigh the anticipated positive effects of resting paddocks. Of course, the overall plant biomass of all paddocks in a cycle (mean biomass) as recorded at end of the season depends on a combination of stocking rate and number of paddocks cycle.

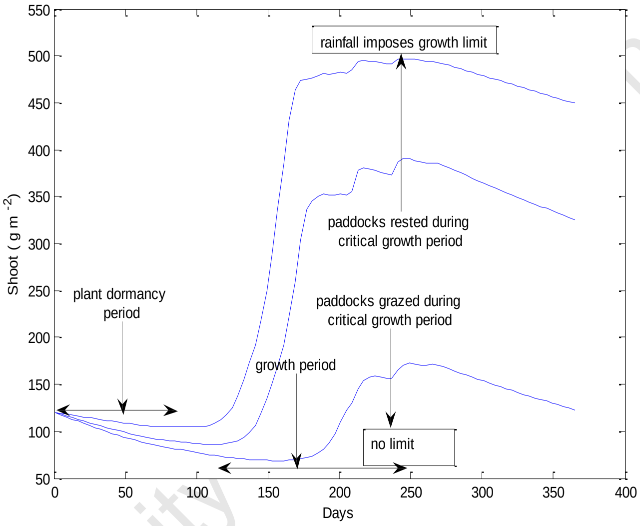

FIGURE 5.19: Illustration of how rainfall constrains the performance of rotational grazing. The simulation was run with the 1980 rainfall data. The upper trajectory was run with no grazing animals. Stocking rate for the lower curve 0.5 and 0.2 steers/ha for the middle curve.

Given influence of rainfall, the performance of rotational grazing requires proper timing of grazing schedules. This is extremely difficult when a rigid schedule of grazing individual paddocks is adopted. On the other hand, when flexible schedules are followed by way of tracking plant development, short period of stay in individual paddocks is critical (Experiment 2.1; Figure 5.7a-c; Figure 5.14a-c).

Second, rainfall inhibits the potential benefits of rotational grazing by imposing the length of plant growth period. This period is highly variable but generally very short depending on rainfall onset and its termination in the year. In semiarid areas there can be several but short storms or fewer intense storms. Growth is initiated when soil water in the second soil horizon is above 50 mm (Dye et al., 1982; Dye, 1984; see Chapter 3 & 4 of this thesis). Yet, there is a time lag in growth from the first storms to the time

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growth is initiated. Because the first two months or so are generally dry, growth period is short. The implication is that with strict schedules of grazing, the efficacy of increasing the number of paddocks in a rotational cycle can be hard to achieve. Notably, this provides a plausible explanation why forage biomass at the end of the season does not correlate with the number of paddocks in the rotational cycle (Figure 5.4). Increasing number of paddocks was expected to provide for longer rest period and short period of stay. Since the period of growth is short, the period of recovery from defoliation effects is also short. However, this could be modified by implementing flexible grazing schedules in individual paddocks to allow for short grazing periods (less than 14 days) during the early part of the plant growth period (Figure 5.7b). In addition, in a heterogeneous pasture following availability and growth rates in various areas generates desirable results (Figure 5.14a-c).

Third, the influence of inter-annual variation in rainfall emerged with very interesting results (Figure 5.8). It was shown that, during the first season of 1980/81 rainfall, the differences between paddocks defoliated at different times of the year were remarkably different. However, by the end of the next season 1980/81, these differences dampen down due to severe defoliation. A characteristic feature of the two seasons is that the 1979/80 year was generally wet while the following season was very dry. Therefore, this finding is not surprising since annual net primary biomass fluctuations are buffered if wet, more productive years alternate with dry, less productive years, and they are amplified if wet or dry sequences of several years take place (Oesterheld et al., 2001). Nevertheless, at a farm scale (overall) the influence of the rotational grazing system on grass biomass remained higher than grass biomass produced under continuous grazing.

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b) The influence of Stocking Rate and Number of Paddocks in a Cycle

Clearly, there was both stocking rate and grazing-rotation effects on plant responses presented in the results. Analyses under a homogeneous pasture suggested that, proper coupling of stocking rate with number of paddocks in a cycle emerged one of the most important managerial tasks required to minimize the effects to realize the benefits of rotational grazing particularly with respect to plant production (Experiments 1.1 & 1.2; Figures 5.1, & 5.3) . In a three-paddock system, differences between shoot biomass under RG and CG became dicernible when stocking rate was set very high and far above the recommended stocking rate of 0.3 steers ha^{-1}. Apparently, at low stocking rate, in the same three-paddock system, there were no observable differences. Contrary, in a six-paddock system, irrespective of stocking rate, the mean shoot biomass under CG was consitently higher than mean biomass under RG. Clearly, stocking rate, number of paddocks are important factors determing these outcome. Perhaps, the experiments could have given more interesting results with large number of paddocks per herd preferable, usually 30 or more, and grazing periods are 7-10 days or even less, so rest periods are automatically long (Teague et al., 2009b).

It is obvious that there is nothing magical about the coupling of number of paddocks and stocking rate *per se*. Rather, there are two critical processes influencing the outcome of RG when comparing with CG. Importantly, high stocking rate under CG in the three-paddock system exerts severe defoliation effects resulting in huge reduction of shoot biomass. Equal stocking rate subjected to a rotational grazing reduces defoliation effects on plant growth largely because of partial resting of the pasture; hence the paddock system emerged an effective strategy (Figure 5.1). In general, very high stocking rate with few paddocks, rotational grazing exhibited both positive and negative effects on plant growth in individual paddocks. But the positive effects outweigh the negative effects. Under the six-paddock system, grazing intensity increases as the number paddocks increase. When strict schedules of grazing paddocks were followed, a number of paddocks in the rotational cycle coincidentally operate within the critical period of plant development. This system brought about both positive and negative effects on plant growth. The negative effects were a result of defoliation at critical periods of plant growth and the positive effects were a result of resting paddocks. However, when evaluated the negative effects outweigh the positive effects. Eventually, compared with CG grazing, the overall defoliation effects under RG outweigh those under CG. These findings suggest that depending on stocking rate few paddocks have inconsiderable effects on plant production. Contrary, many paddocks increase grazing pressure and defoliation effects in paddocks grazed during critical period severely intensify.

The relationship between stocking rate, number of paddocks and plant production is well established in the literature Noy-Meir (1976). Noy-Meir showed that moderate rotation, with few subdivisions and short cycles, had only minor effects on plant productivity, compared with continuous grazing. Intensive rotation (many paddocks and/or long cycles) resulted in a decrease in long-term productivity when the stocking rate was moderate and the initial plant biomass of the pasture high. When the stocking rate was high and the initial biomass of the pasture poor, but an ungrazeable residual was present, intensive rotation substantially increased the long-term plant productivity compared with continuous and moderate rotational grazing.

It was shown that with few paddocks increasing stocking rates under RG does not have adverse effects on plant production (Figure 5.1). A similar study carried out by Denny & Barnes (1977), and Barnes & Denny (1991) in the same study area did not report any effect of grazing treatment on the condition of the vegetation. The strength of their study is that it was conducted a long period of eleven years. Inspired by these findings Norton (2003) hypothesized that stocking rate can be substantially increased beyond what is generally recommended as the optimum carrying capacity for this kind of rangeland, increased to even double that recommended rate, without imposing adverse impact on the condition of the resource. Our findings on a three-paddock system showing that at the rate of 0.6 steers/ah shoot biomass under RG was higher than biomass under CG would seem to be reasonable evidence in support of this inference.

The benefit of increasing number of paddocks was that the period of stay in individual paddocks became shorter. This combined with resting paddocks during the early period of plant growth allowed for plant growth to the maximum limited by rainfall in the absence of grazing. Consequently, the negative effects of increased stocking rates combined with defoliation during the early days of plant growth from paddocks outweighed those positive effects emerging from the other paddocks. Eventually, when implemented with many paddocks the potential benefits of rotational grazing in terms of plant growth arising from short period of stay diminished (Figure 5.4). The length of grazing and rest periods has great influence on the performance of RG. For example, repeating grazing periods in the same paddock within the same year reduces the effects defoliation as grazing pressure is distributed over time and space (Figure 5.7a, b, c).

c) Interactive Effects of Rainfall, Grazing Intensity, Timing And Grazing Period

Analyses presented here, further indicate that the interaction between rainfall and grazing influence shoot peak biomass as well as biomass at the end the year. In addition, the peak shoot biomass within season is highly variable depending on stocking rate and grazing management procedure (Chapter 4; Experiment 1.1 – Experiment 1.4). Values range from 120.0 to 500.0 g m $^{-2}$ in single paddocks, and 275.0 to 400.0 g m^{-2} under RG and CG. Fynn & O’Connor (2000) studied a two-paddock rotational grazing. They found that depending on the amount of rainfall in a season, herbaceous biomass under rotational grazing of two paddocks stocked at low, medium and high rates, respectively, ranged from 2.4 to 3.7, 2.1 to 3.5 and 2.1 to 3.2 t/ha at one site, and 2.5 to 3.6, 2.2 to 3.3 and 2.0 to 3.7 t/ha at another.

Although our simulation is on a single season of the 1980 rainfall data, the figures are relatively within the same range when converted to the same units of measure (g m^{-2}). Nevertheless, the upper limit of shoot biomass in the current study is reasonably higher for reasons related to site-specific differences such as plant species and soils. Fynn and O'Connor considered herbaceous plants whereas the current modelled grass species of semi-arid savannah. Probably, the differences in annual rainfall have also effects since the simulations here used rainfall data for 1980 while the former study covered a period from 1986 to 1996. All the same, variations in peak shoot biomass in the current study are an interesting observation attributable to the influence of rainfall, and grazing intensity and timing of grazing.

Importantly, the timing of grazing in individual paddocks played a very important role. When strict grazing schedules were followed with many paddocks; the number of paddocks in a rotational cycle determined both the period of stay and size of paddocks. Increasing the number of paddocks in the rotational system increased grazing pressure in individual paddocks as the sizes of individual paddocks reduced. Interactively, rainfall limits the length of plant growth period while very high stocking rates and grazing paddocks during the early stages of plant growth retard plant growth which consequently further shortened the growth period (Figure 5.2a-c; Figure 5.16**).** Consequently, the period for plant recovery after defoliation is also short as most part of the season is dry. Reducing the period of stay minimized the effects of early defoliation resulting in higher shoot biomass under RG than CG (Figure 5.7b). These findings support the contention that timing of grazing periods according to plant growth rates is of central importance to the success of short duration grazing (Savory, 1983; McCosker, 1994; Barnes et al., 2008).

d) Scale-Dependence of Plant Responses to Rotational Grazing Systems

Intensive rotational grazing (IRG) has been advocated as widely applicable for restoring rangeland productivity, but some in the rangeland science community have denounced it (Holechek et al. 2000; cited by Barnes et al., 2008). The recent synthesis of grazing systems has shown that there are no superior benefits of rotational grazing over continuous grazing (Briske et al., 2008). Specifically, field studies have shown that harvest efficiency was not improved by short rotational grazing (Heitschmidt, 1987a).

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Nevertheless, many studies overlook variations in plant responses in individual paddocks. At what spatiotemporal scale does one grazing system perform better than the other? Analyses presented in this study clearly showed that the performance of a grazing management procedure specifically in terms of plant production largely depends on the spatial scale of measurement (Figure 5.1-5.3; Figure 5.17).

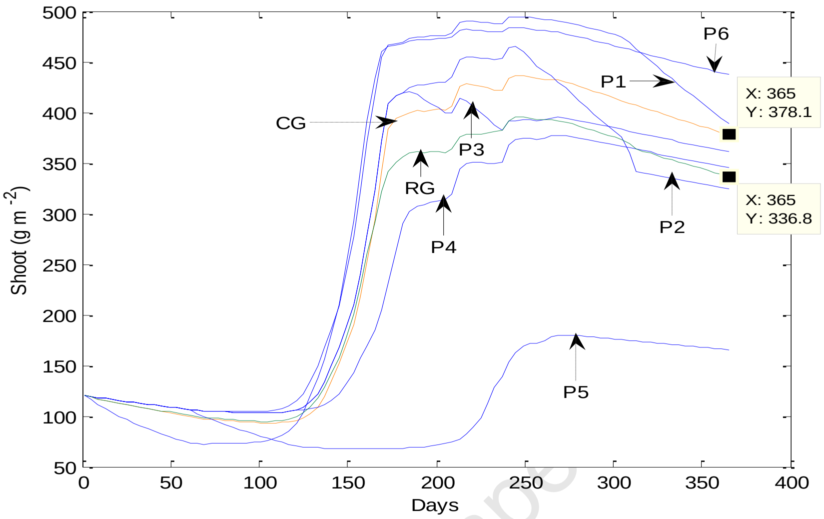

FIGURE 5.20: A six-paddock (P1 – P6) response to RG and CG stocked at 0.3 steers ha -1 and simulated with 1980/81 rainfall data. RG and CG are measured at the scale of whole farm (1000 ha). Paddock are measured at the small scale (167 ha).

This study suggests that plant responses to rotational grazing are scale dependent, but the role of spatial scale may differ among paddocks depending on timing and intensity of grazing, besides the period of grazing. For example, overall, at a large scale of a farm (1000 ha) shoot biomass under CG is clearly higher than shoot under RG (Figure 5.20). Even though, at a smaller spatial scale of P6 (167 ha) shoot is higher than both other paddocks of equal area and CG (i.e. grazing at whole farm 1000 ha). Higher shoot biomass in CG than RG is largely a result of P5 being severely defoliated. When computing the mean of all paddocks (P1-P6), the positive effects of other individual paddocks diminish. However, from management perspective, a localized effect like this should be relatively more manageable than a widespread effect resulting from widespread occurrence of selective grazing under continuous grazing. This finding holds management implications as will be discussed in Chapter 6.

Similarly, the need for consideration of the temporal scale of measuring the effects of a grazing management procedure applies. It has been shown that three paddocks rotationally grazed for two years indicated discernible differences in terms of

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plant biomass during the first year. Later in the second year, these differences disappeared. This is an important observation in experimental studies as ecologists struggle with the question about how long rangeland experiments must continue in order to detect treatment effects, particularly in semi-arid rangelands which are characterized by slow responses and high spatiotemporal variability (Mashiri et al., 2008).

In relation to rainfall in the two years; would differences between years persist at light stocking rates? Analyses in this study clearly showed differentiated responses among paddocks in a rotational grazing system depending on when measurements are taken. However, under continuous grazing (whole farm), the differences between rotational and continuous grazing largely depend on stocking rate and number of paddocks in the rotational cycle. If different variables such as change in species composition were examined, different time as well as spatial scales of observation would be required. It is not surprising that some field studies on rotational grazing systems present contrary results on plant responses. The most possible explanation may suggest that detrimental grazing impacts on plants are more likely to be measured at smaller spatial and temporal scales. Over a period of several days or several weeks grazed plant growth can prove to be less than ungrazed plant growth (Coughenour, 1991). Over a year, however, the grazed plants could compensate for their losses because limiting nutrients are recycled at a faster rate by herbivores (MacNaughton, 1979; 1984; Coughenour, 1984). Nevertheless, in extensive systems insufficient nutrient recycling may not be important at low stocking rates.

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e) Recovery of Paddocks From the Effects of Defoliation

A three-paddock system simulated for two subsequent years showed that paddocks grazed during the early part of the first season were severely affected by grazing pressure (Figure 5.8). In the subsequent year the most severely affected paddocks recovered. This observation is in line with other studies (e.g. Teague & Dowhower, 2003; Teague et al., 2004). Teague & Dowhower (2003) examined the ability of rotational grazing to reduce degradation caused by patch-selective grazing in large (1 800 – 2 100 ha) paddocks in the rolling plains of Texas. The eight-paddock rotation increased herbaceous basal cover and decreased bare ground relative to CG. Both treatments exhibited improvement during favourable growing conditions, but the improvements were significantly greater in the rotational grazing treatment, where there was also less deterioration during drought (Teague et al. 2004).

f) Subsequent Re-Growth and the Role of Roots and Carbohydrate Reserves

The results in this study have shown that the severity of defoliation under continuous grazing affects re-growth (Figure 5.8). The role of roots in forage growth relates to their functions as important organs used to absorb water and nutrition from soil, and as storage organs for organic matter (Snyman & Du Preez 2005), and carbohydrate reserves the manufacturing organs for various hormones and growth regulators. Defoliation severity affect water-soluble carbohydrate levels, as indicated by residual height of stubble (Troughton, 1957; Davidson & Milthorpe, 1966; Wilson & Robson, 1970), as well as the interval between defoliations (Bell & Ritchie, 1989; Fulkerson & Slack, 1995; Turner et al., 2007).

g) Pasture spatial variability and Planned Grazing

Recent arguments which support the use of grazing systems point towards the need for being aware of the spatial variability of the grazing environment (Norton, 2003; Barnes et al., 2008; Teague et al., 2009). The analyses considered both heterogeneous and homogeneous pasture with results on plant responses markedly different, largely in favor of RG in heterogeneous pasture largely in terms of forage quantity at the end of the season (Figure 5.14a-c). These findings are however, at variance with the works of Gammon & Roberts (1978) and O'Reagain & Turner (1992) who reported that forage quality and quantity were not consistently and substantially increased in intensive systems compared to CG. The results indicate substantial differences in forage biomass between RG and CG.

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5.6.2 Animal Responses to Grazing Management

The study suggests that there is merit in evaluating grazing management procedures by measures of gain per animal. This is in contrast to plant responses presented in this study or measures of changes in plant species composition (e.g. Denny et al., 1977). Current results have shown that irrespective of the stocking rate gain per animal at the end of the year was consistently higher under rotational grazing relative to continuous grazing procedure (Table 5.2-5.4 & Figure 5.15). The higher weights under rotational grazing were observed at low stocking rate, although one highest value was observed under high stocking rate. This could have been an outlier.

Reasonably, the values of weights as obtained at the end of the season are similar to the results by Fynn & O’Connor (2000). They studied a two paddock rotational grazing; depending on a season's rainfall, gain per animal for low, medium and high stocking rates, respectively, ranged between 113.0 and 225.0 kg; 82 and 220.0 kg; and 102.0 and 217.0 kg at one site. Moreover, at another site, with the same stocking rate, values ranged between 151.0 and 241.0 kg; 103.0 and 225.0 kg; and 76.0 and 215.0 kg. The initial weight of individual animals in this example was also 250.0 kg. Thus, approximately the overall range of weight at the end of each season before replacing the animals with new ones in the next season was between 250.0 and 500.0 kg.

Second, resting of paddocks in the grazing schedule ensured that forage availability increased from paddock to paddock along a seasonal gradient. Eventually, available forage in the paddocks satisfied individual animal nutritional needs. Like in other studies, this finding further suggested that the spatial scale of management may play an important role in determining the sustainability of secondary productivity (Fynn & T.G. O'connor, 2000). In addition, despite some paddocks experiencing a decline in plant production, these paddocks recovered in the next growing season unlike biomass under continuous grazing (Figure 5.8). Moreover, even if overgrazed paddocks did not recover from severe defoliation the benefit of rotational grazing would still arise from those paddocks which abundantly produced plant biomass. Fynn & O’Connor (2000) observed that the rotation of cattle between two paddocks at high stocking rate allowed a non-degraded paddock to offset any forage shortages in degraded paddocks during a dry period. These are interesting findings with great implications for adaptation of semi-arid rangelands to climate change as discussed in Chapter 6.

Denny et al. (1977) established that in terms of nutrition, rotational grazing did not appear to be of particular benefit during the dormant season. This conforms to results, which demonstrated that during the first 80 or so days before it started raining, animals rapidly lost weight under both continuous and rotational grazing (Figure 5.17). The cause of this was unavailability of the green material leading to low intake and low digestibility of the selected diet. However, the loss under rotational grazing was more severe than under rotational grazing. Nevertheless, this is a problem largely determined by the timing of rainfall.

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The disagreement between the current study and the former emerge from their overall conclusions on animal biomass in relation to number of paddocks and stocking rate. They compared a four-paddock system stocked at 5.4 ha per steer (0.185 steers/ha) and a 12-paddock system stocked at one steer 3.4 ha per steer (0.294 steers ha^{-1}) and established that the performance of individual steers in the 12-paddock system was depressed compared with individual steers in the four-paddock system. This is contrary to current findings, which showed that individual animals gained more weight with increasing number of paddocks in the rotational cycle even at the high stocking rate (Table 5.2-5.4; Figure 5.15). Ideally, the study should have further tested the animal responses beyond the period of one year. However, animal responses largely depend on the initial available forage at the beginning of each year. It was shown that using the 1980 rainfall data with three paddocks, shoot biomass at the end of the season was still higher than shoot under rotational grazing. Having established responses for a single year, it should be possible to extrapolate the results beyond a single season. Reasonably, individual paddocks would have produced more forage than the whole farm under continuous grazing even after five years.

5.7 Conclusions

The following specific objectives are addressed in this chapter:1) determine the combination of stocking rates and number of paddocks that result in better performance of a rotational grazing system 2) compare responses of plant and animals to continuous and roataional grazing systems. The chapter has demonstarted how complicated interpretation of plant respones to a grazing system can be. Results showed that lower stocking rates irrespective of the number of paddocks in the rotational cycle yielded better results in terms of plant production. However, in comparison with continnuous grazing, distinguishable differences were not observed. This result is sufficient to conclude that there is no reason to prefer a particular grazing management procedure at lower stocking rate if the objective is exclusively to improve plant production. As regards animal responses, rotational grazing consistently demonstrated better than continuous grazing with increasing gain as number of paddocks in a cycle increased. This suggested effiency in dry matter intake with incresaed animal biomass in small paddocks.

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At medium and high stocking rates, the performance of rotational grazing, with respect to plant production, depended on the correct combination of stocking rates and number of paddocks in the rotational cycle. There was no single way to describe how that should be done. Gnerally, if grazing and resting of individual paddocks follow strict schedules in accordance with number of paddocks in the cycle, successful implementation of rotataional grazing was found to be extremely difficult to achieve. While the idea of period of rest is important, the period is not necessarily and an important detrminant. Rather, the timing and intensity of grazing are significant factors that dtermine the outcome between rotational and continuous grazing with respect to plant responses. Results showed that rainfall interacts with grazing to inflence seasonal growth period and the maxium plant biomassin indvidual paddocks of the rotational cycle. Better results were observed when timing and intensity of grazing were correctly combined. Besides, the outcome of rotational grazing in subsquent years from previous years is largely influenced by preservation of carbohydrate resvers. The implication is that in semiarid rangelands, studies of rotational grazing systems are susceptible to variable findings depending on such factors as the combination of number of paddocks in a cycle, timing of grazing and stocking levels .

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Chapter 6

Synthesis, General Discussion, and Management Implications

6.1 Introduction

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One of the major obstacles to sustainable management of semi-arid/arid rangelands is a consequence of low and highly variable rainfall. During dry years, forage becomes scarce and availability controls intake as animals have little choice. During years of high rainfall a large part of the forage decomposes as cattle consume only limited areas that are grazed heavily. Excessive defoliation of the most preferred species can lead to long-term decline in their productivity, and eventually to the poor performance of the entire grazing enterprise. The use of rotational grazing systems as management options needed complementary work as justified on two strands of argument. The first, proposed the need to extend our knowledge of the system dynamics to the most appropriate scale of grazing management units such as grazing paddocks. The second argument speculated possible problems involved in execution of field trials, and hence the need for the modelling alternative. Along these arguments, the general objective was two-fold: 1) to increase our understanding of the dynamics of a semi-arid savannah rangeland focusing on three levels – the plant, paddock and whole-farm 2) in order to re-examine grazing systems with modelling as an extension to field trials. This goal was achieved with prior chapters as key study outputs.

Chapter 2 presented a detailed review of the grazing literature, which concluded that rejection of the use of grazing systems in rangeland management is premature. The review argued that, the potential exists to demonstrate that rotational grazing systems enhance both plant and animal production. The failure to illustrate the same, by some previous works, requires that field trials pay attention to a multitude of interacting factors. These factors include the influence of rainfall and the need to synchronize with grazing schedules, consideration for experimental designs, and proper combination of stocking rates, paddock size and number of paddocks in the rotational cycle, as well as pasture characteristics. These factors have apparently received a cursory attention in studies of rotational grazing systems. The review further identified the savannah model (Richardson, 2000) as one of the most suitable to use to address the research question.

Adapted version of the savannah model, its structure and the basic mathematical assumptions were described in Chapter 3. Subsequently, the model was tested for its performance with regards to predictions of plant growth in response to seasonal and inter-annual rainfall in combination with various stocking rates (Chapter 4). Using the model, Chapter 5 simulated two different grazing strategies such as continuous and rotational grazing. Plant and animal responses were compared between the two grazing management procedures, the outcomes of, which largely depended on the design of the rotational system, stocking rate and pasture characteristics.

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6.2 General Discussion

This is the last chapter synthesizing the research findings and discusses the extent to which the study has addressed the key research question. To begin with, a critique of the methodological approach is provided. Subsequent sections deduce the implications of the key findings in light of theory, policy and management of arid/semi-arid ragelnds. To conclude, the chapter draws attention on gray areas for further research.

6.2.1 Methodology Critique

Like any other mathematical model, the equations presented in the Richardson Savannah Model (Richardson, 2000) are simple caricatures of the ecological processes under consideration. The most important success of the model is the inclusion of the dominant processes pertinent to understanding the dynamics of semiarid ecosystems, such as rainfall-plant-animal interactions. There are reasons for believing that the equations used capture some aspect of reality. The model is able to link predictions of soil water dynamics in response to rainfall and its influence on plant growth at various spatial-temporal scales. Model evaluation relied on both expert opinion and published literature (e.g. Dye, 1984; Fynn & O’Connor, 2000). The model reasonably predicts the influence of rainfall amount and distribution in plant growth over time in two fundamentally different ways (Figure 6.1):

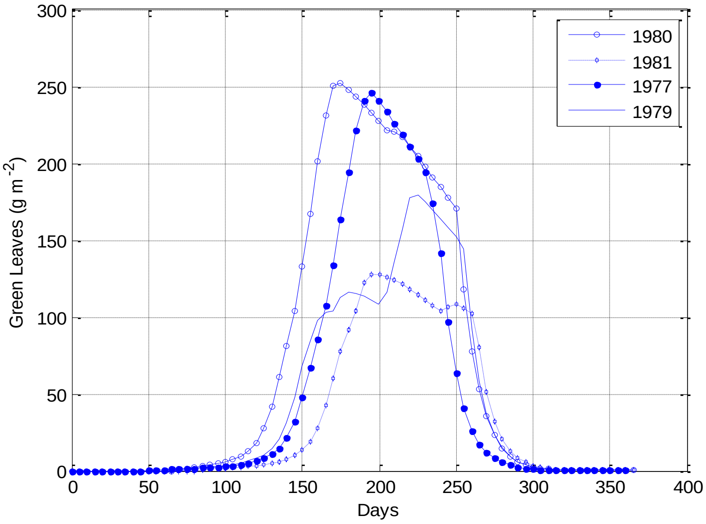

FIGURE 6.1: Model prediction of green leaf biomass using rainfall data for different years (1977, 79, 80 & 81). Green leaf biomass varies according to the annual cumulative rainfall between years and along a seasonal gradient.

Firstly, rainfall limits the rate of plant growth, and consequently, affects forage yields varying from season to season depending on the cumulative annual rainfall of the particular year. Secondly, rainfall determines the period of plant growth thereby constraining forage availability along a seasonal gradient and across years. In semi-arid systems these observations are documented (cf. Dye, 1984). This system behaviour concomitant with stocking pressure affects the long-term productivity of rangelands, although the study explored the short-term dynamics only. To this end, the model was convenient. Nevertheless, a number of drawbacks are inherent in the model structure, its implementation as well as the assumed parameter values.

Firstly, the basic assumption of a single global plant species suggested in the model structure limits its usefulness to savannah grasslands largely with homogeneous vegetation. Thus, the effects of continuous grazing resulting from large scale grazing selection could have been missed out. Hence, Section 5.3 of the simulation experiments used the model to compare the efficiency of harvesting forage between continuous and rotational grazing, rather than the effects of larger scale spatial selective use such as patch grazing (Teague et al., 2004). However, simplistically though, a heterogeneous pasture with a productivity gradient was simulated, and interesting results emerged. The model could have been adapted further to simulate more than one species. Nonetheless, the model assumes grazing selection at a plant scale. This approach was perceived satisfactory since rangeland degradation attributed to overgrazing is largely a process operating on the small spatial scale of individual plants at the temporal scale of

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defoliation events (Coughenour, 1991). The effects of grazing become visible only at large time scales of often decades as a result of small spatial scale effects. Thus, the approach focused on cumulative forage production since in non-equilibrium systems animal production is closely related more to total herbage production than the species composition of pasture (Ellis & Swift, 1988; Mentis et al., 1989; Wilson, 1991; Hodgkinson, 1992; Pickup, 1996).

Secondly, the model has been used to evaluate grazing management procedures using historical rainfall data of only 1980/81 and 1981/82 seasons, although Matopos would supply later data on request. Grass growth data are used for 1978/9 to 1982/3 in Dyes thesis, and therefore using these data sets was necessary for comparison. Thus, two and a half decades have passed since the last year of available data for the study area. As such, seasonal climatic conditions might have changed with the possibility of shifts in the dynamics of seasonal forage production. The importance of model validation with field data is recognized, but this could not be done within the limited timeframe of the study. Alternatively, following Bosman et al. (1997), the model was tested by way of operational and technical evaluation. The model exhibited accurate representation of the real world from the perspective of the qualitative behaviour, and served the intended use.

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6.2.2 Key Research Contributions

One of the key gaps in the rotational grazing literature as was identified in this research is the scarcity of modelling studies. The simulation analyses presented by the current study make a different kind of contribution, first to the understanding of the dynamics of semi-arid rangelands, and second evaluation of grazing systems. The model enables internal processes not readily measured in the field to be simulated and appropriate estimates made. Nonetheless, if the study has produced some new or interesting conclusions with respect to evaluation of grazing systems, it remains to be asked: *to what extent?* The study produced mixed results on plant responses, the outcome of which largely depended on the right combination of stocking rate and number of paddocks in a rotational cycle, as well as the period of grazing in individual paddocks, besides pasture characteristics (homogeneity vs. heterogeneity). Therefore, the objectives of the study have been achieved to certain extent and some important contributions have emerged as follows:

a) On the Spatiotemporal Dynamics of Rangelands

The first objective was to increase our understanding of the spatiotemporal dynamics of the rangeland at scales of grazing management units. The most remarkable outcome of this objective is the detailed knowledge generated on plant-animal responses in particularly in individual paddocks of different sizes in area, the effects of the timing and period of grazing, in addition to pasture characteristics (homogeneous vs. heterogeneous). Fixed schedules of grazing along a seasonal gradient documented that the number, and therefore sizes of paddocks in the rotational cycle, interactively influence the intensity and timing of grazing; and eventually influence plant-animal responses (Chapter 5; Experiments 1.1-1.4). On the influence of rotational-cycle and intensity of grazing, the current study showed interesting results on the relationship between the timing of both rainfall and grazing and maximum plant growth, and how these two factors control the outcomes of studies on rotational grazing systems (Figure 5.1-5.3). The importance of this finding relates to applicability of rotational grazing in semi-arid systems as belated onset of rainfall shortens the period of growth, thereby affecting the effectiveness of grazing systems. Short periods of grazing (6-10 paddocks) in individual paddocks reduce defoliation impacts on plants especially those paddocks subjected during critical period of plant development. This is largely because, the short periods the effects are short-living and also allow for more time for recovery (Figure 6.5).

b) On The Performance of Rotational Versus Continuous Grazing

The second part of the general objective was to re-evaluate the performance of rotational grazing systems and continuous grazing based on plant and animal responses in individual paddocks in the cycle in response to timing and intensity of grazing (Table 5.2-5.4). While the results on plant responses were mixed, strikingly animal gain was interesting. Generally, live individual weight gain was highly variable within a year in response to forage availability, stocking rate, and grazing management procedure. Animals lost more weight during the dry season under rotational grazing than continuous grazing. The findings of this study provide rare evidence that resting a pasture and the timing of grazing are sound, more than ever when stocking rates are excessive. For example, in a six-paddock system the impact of grazing a paddock at the

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critical period of plant development retards growth and, eventually forage availability in time. In terms of animal performance, the study establishes that rotational grazing is a viable option. The benefit comes primarily as a result of the accumulation of green material over a longer period which provides for increased daily intake by individual animals (Table 5.2-5.4). With sufficient rainfall the use of multi-paddock systems with high stocking rate enhances efficient harvest of the forage. However, when rainfall is low, two to three paddocks could be used as a means to preserve forage (Figure 6.2 & Figure 6.3). Longer period of resting paddock would reduce the impact of grazing at the critical period early in the grazing season.

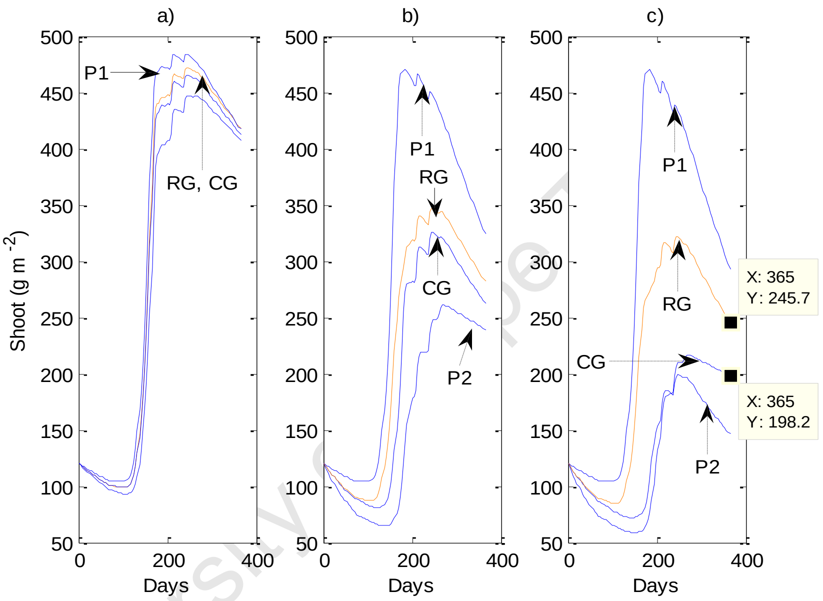

FIGURE 6.2: Prediction of shoot in P1 & P2, rotational grazing (RG) and continuous grazing (CG) with stocking rates (steers/ha) of a) 0.15 b) 0.6 & c) 0.75. Animals graze P1 during half of the season before moved to P2. When rainfall is low, RG should be used to preserves forage.

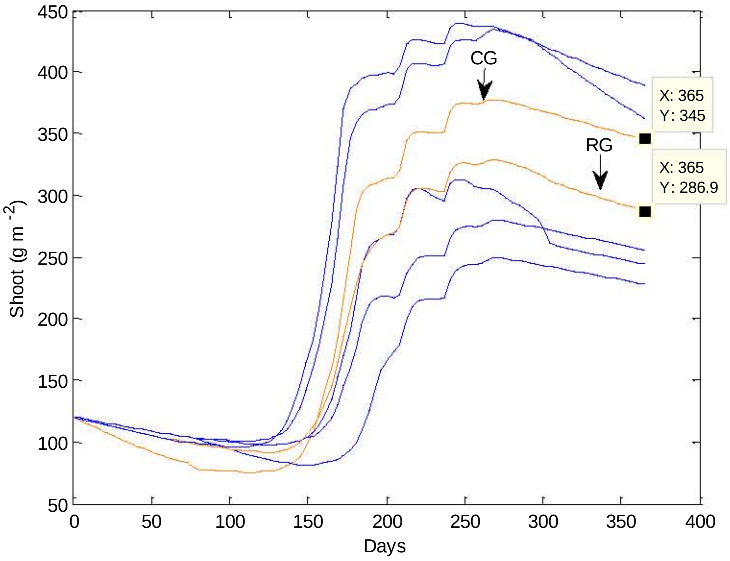

FIGURE 6.3: Prediction of shoot growth in a five-paddock system with a stocking level of 0.175 steers/ha. Shoot biomass is lower under RG than CG. When rainfall is high RG should be used as an efficient harvest of forage.

Lastly, one important mechanism to explain the potential benefit of rotational grazing systems concerns the dynamics of root biomass and carbohydrate reserves as influenced by grazing intensity. Under rotational grazing, both root biomass and carbohydrate quantities were higher under rotational than continuous grazing. This is an exceptional finding in the study of rotational grazing systems. The importance of understanding root and carbohydrate reserve responses to a grazing system is relevant as the former influences plant competitive potentials (Snyman, 2009) while the latter influence grass re-growth. With this set of knowledge the ultimate research question can be attempted.

6.2.3 A Response to the Ultimate Research Question

On the basis of the knowledge about the interaction between variable rainfall and grazing at the scale of grazing management units, what practical improvements to the design of rotational grazing systems are necessary?

First, the study suggests that there are many benefits to attribute to the use of rotational grazing systems depending on the choice of management objectives and the spatiotemporal scale of measurement (cf. Chapter 5, Section 5.5.1). Second, the study demonstrated mechanisms that control the performance of rotational grazing systems including rainfall distribution in time and the intensity and duration of defoliation in both time and space. They should adjust stock movements and grazing events to synchronize in time and space with rainfall and forage availability. To reap the various benefits attributed to rotational grazing procedures, adjustments to conventional way of implementing grazing systems are required.

a) Embrace Multiple and Specific Management Objectives

At a farm scale, the spatial and temporal distribution of grazing is a viable option to achieve the objective of increasing homogeneous use of vegetation by animals in order to control wide grazing selectivity. Notwithstanding this objective, the current study provides insights to the effect that land managers could use rotational grazing to manipulate seasonality of grazing and utilization levels within individual paddocks to achieve a specific objective. The objective is to reduce the effects of intensive defoliation during critical stages of plant growth. Resting paddocks during critical stages of plant growth, or short grazing result in high plant biomass at the end of the season (Chapter 5, Figure 5.1-5.3). Similarly, the literature indicates that rotational grazing at a paddock scale can be a useful tool for rehabilitation of degraded areas (e.g. Teague & Dowhower, 2003; Teague et al. 2004). Moreover, as climate change is inevitably impacting many production systems, rotational grazing procedures are prospective adaptation measures as discussed later in this chapter. These arguments lead to suggest that implementation of rotational grazing systems should embrace an adaptive approach by adopting a wide range of objectives to achieve both immediate production objectives while aiming at long-term sustainability of the production system.

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b) Adopt Flexible Grazing Schedules with Variable Stocking Rates

Grazing intensity, the impact upon forage by animals, largely dictates the influences of livestock grazing on rangeland vegetation (Fuhlendorf & Smeins, 1997). Analyses presented here, showed that paddocks grazed during the period of plant dormancy even at high stocking rate of 0.3 animals ha $^{-1}$ is of no negative consequences (Figure 5.1-5.3). Fortunately, the dormant period in semi-arid systems is very long although variable (cf. Dye, 1984). Subjecting the pasture to rotational grazing at very low stocking within this long period of dormancy has little benefit to the grazing system (Figure 5.1a, b). Although the overall gain in weight of individual animals was satisfactory (Table 5.2-Table 5.4; Figure 5.15), the initial loss of weight under rotational grazing was higher than loss under continuous grazing during the dormant part of the season (Figure 6.2).

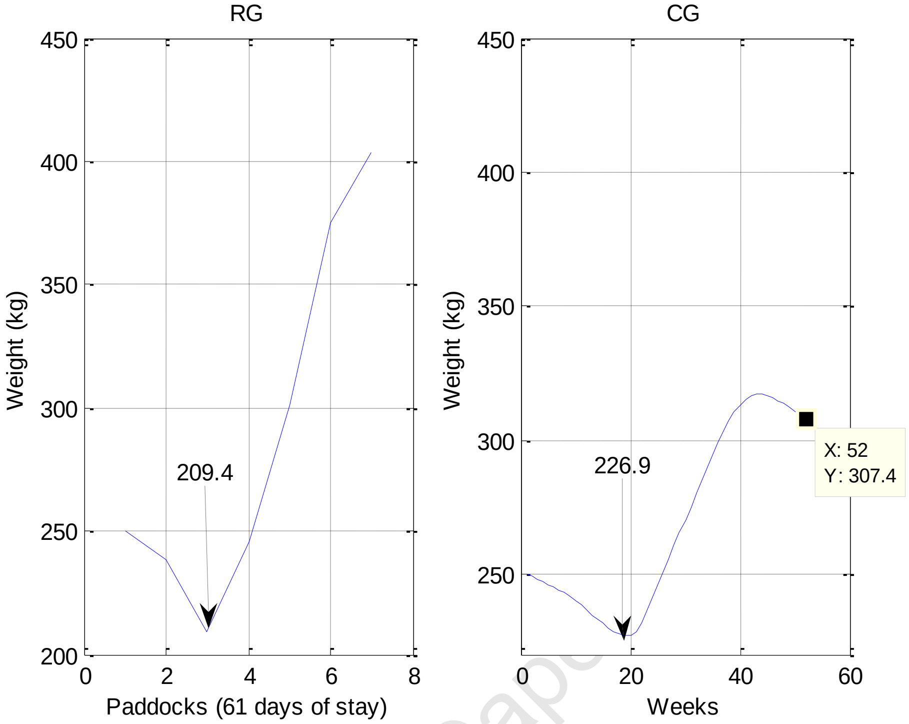

FIGURE 6.4: Animal responses in a six-paddock system grazed rotationally compared with continuous grazing. Under rotational grazing animals lose 40.6 kg during the first 100 days or so compared to 23.1 kg lost under continuous grazing at a comparative stocking rate of 0.2 steers ha^{-1}. Managed grazing can improve gain in individual animal weight by implementing CG during the dormant period and RG during the rest of the season.

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Therefore, one important window of opportunity arises with the potential to reverse the initial loss of weight during the dormant period and improve animal performance. During the dormancy period the pasture should be utilized continuously with medium or high stocking rate. This can substantially reduce the weight loss under rotational grazing (Figure 6.4). When the initial forage at the beginning of the season is abundant and that there is anticipation for plenty rainfall, rotational grazing could be utilized to ensure optimum plant growth and to facilitate efficient harvesting of the forage. However, if inadequate rainfall is anticipated, which of course is unpredictable, this might prove harmful as increasing the stocking rate beyond the recommended level could greatly affect paddocks grazed when the plant-growing period starts. However, using short grazing periods at this time will yield desirable results (Figure 6.5). Warren et al.(1986d), in a study on the effects of season and stage of rotation cycle on hydrologic condition of a rangeland under intensive rotational grazing recommend that during winter dormancy or during drought periods lower stocking rate and/or longer rest periods should be adopted. Nevertheless, during years of plenty rainfall, the temptation to increase stocking rate is desirable especially when such rainfall come in consecutive years (Dye, 1984).

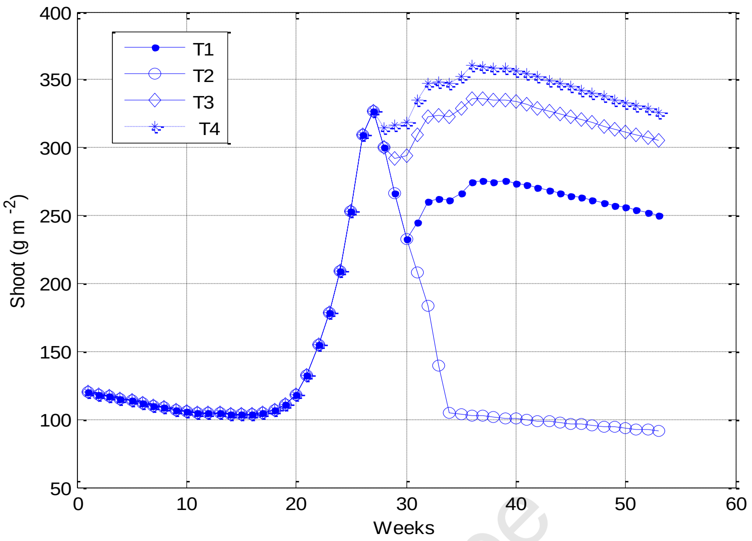

FIGURE 6.5: Plant responses to a period of grazing (T1 = 22 days; T2 = 45 days; T3 = 15 days; T4 = 10 days) within a critical period of plant growth with medium pasture productivity. This simulation was purposely run with a very high stocking rate of 0.65 steers/ha in zone 2 (cf. Experiment 2.1). Shorter periods ameliorate the effects of defoliation which result from grazing critical periods of plant growth.

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c) Synchronize Grazing Events with Plant Growth Rates in Space

Rotational grazing management can be improved by making periods of stay as short as possible. This is true when grazing in paddocks is scheduled take place during a critical period of plant growth (Figure 6.5). Longer periods of stay during this period especially with heavy stocking results in unprecedented decline in forage production. Importantly, grazing events in a rotational cycle should follow the growth rate and availability of forage. This allows for recovery and prevents the effects of intensive defoliation. More this prescription will ensure that more forage is available at the end of the season under RG compared with CG (Figure 14a-c).

6.3 Theory and Management Implications

While the non-equilibrium paradigm places much weight on the influence of rainfall on rangeland dynamics, this study found that the effects of intensity and timing of grazing interact with rainfall and influences the timing of plant growth and the maximum rate of plant growth (Figure 6.5). While the expected effect of rainfall on aboveground grass production of in a semi-arid savannah was obvious, heavy stocking ultimately had a deleterious influence on primary production in paddocks vulnerable to grazing during critical period of plant growth. For example, irrespective of whether it is a year of plenty or low rainfall, at medium stocking, grazing the first leaf in small paddocks was found to retard growth and eventually the maximum biomass (Chapter 5, Figure 5.2a-c). This was largely due to increased grazing pressure. That aside, from management perspective, the major concern of the new rangeland theory over classic rangeland theory's recommendation of constant stocking is that farmers do not take advantage of high forage production during years of plenty rainfall (Behnke & Scoones, 1993). One management alternative is to force animal numbers track variation in grass production. Unfortunately, the feasibility of these strategies has been very difficult to demonstrate (Illius et al., 1998; Higgins et al., 2007). Higgins et al. (2007) suggest that it is optimal to stock at rates much lower than the potential carrying capacity. High stocking under rotational grazing ensures efficient harvest of the forage while at the same time forage can be preserved in paddocks for the subsequent years. This forage could be used for supplementary feeding in the case of a bad year of low rainfall. However, inspection of Figure 6.6 indicates that for the years 1980 and 1977 rainfall, before day 125 and after 250 grazing has little impact on total biomass of herbage because plant growth is dormant (Figure 6.6).

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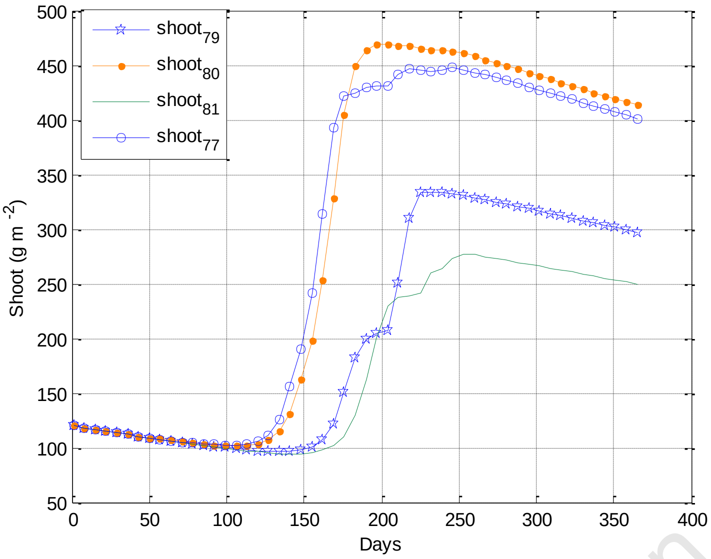

FIGURE 6.6: Variation in initiation of plant growth period depending on rainfall onset. This makes strict schedules of rotational grazing difficult to achieve higher animal production.

This period was even shorter for the years 1979 and 1981. However, the timing and intensity of grazing are very important factors management must take into consideration in order to prevent deterioration of the range. When shorter plant growth period are anticipated, farmers can decide to destock and avoid dry season losses and also sell animals before they lose condition and value. If bush encroachment is a problem in a specific paddock, the accumulated grass could provide fuel for a hot fire to kill woody plants.

6.3.1 Implications for Vulnerability and Adaptation to Climate Change

Range managers have always had a challenging question: How do you balance forage supply and demand by grazing livestock while minimizing risks to degradation when you cannot foresee the future climatic conditions? Although this model does not project rangeland dynamics in response to future climatic changes, rangelands are generally vulnerable with most proximate effects threatening pasture production (Hoffman & Vogel, 2008). The dominant influence of climate change on pasture growth is expected to be changes in the amount of rainfall (Hall et al., 1998; Crimp et al,. 2002). The current study and others (Dye, 1984) have shown that year to year fluctuation of forage production emerges primarily from the effects of variable rainfall. The major window of vulnerability of semiarid rangelands to climate change arise from the undesirable result that rainfall imposes plant growth period (Chapter 5, Figure 5.19). Worse still,

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climate impacts may be severe but they are often exacerbated by current management practices (Hulme, 2005). Underpinning these findings is the assumption that adapting to current climate risks is consistent with adapting to future changed conditions and thus, current knowledge applies to address future risks (Houghton et al., 2001).

The use of rotational grazing provides scope and potentials as adaptation measures to climate change impacts in three different ways. First, resting paddocks during years of adequate rainfall preserves forage for the next growing season while at the same time serving as an efficient means of forage harvest. Secondly, droughts may exacerbate degradation; resting paddocks provides the opportunity for recovery from and reduces degradation caused by patch overgrazing and that planned rotational grazing addresses the root cause of patch overgrazing and deterioration. Teague & Dowhower (2003) examined the ability of rotational grazing to reduce degradation caused by patch-selective grazing in large (1 800– 2 100 ha) paddocks in the rolling plains of Texas. The eight-paddock rotation increased herbaceous basal cover and decreased bare ground relative to continuous grazing. Nevertheless, related adaptation to climate change would require an integrated approach of these strategies with other robust measure adopting stocking destocking strategies.

6.3.2 Implications to Various Stakeholders

Rangeland ecology endeavors to provide guidance on how to reduce uncertainties for people who are making decisions to ensure long-term productivity of rangelands. There are two main categories of decision makers seeking information. One group includes managers, farmers, ranchers, and agribusiness. The other group comprises regional, national or international policy makers seeking to develop an appropriate, evidence-based legislative and regulatory environment. In one way or the other, all these categories may benefit from the findings contained in this study. However, generalizations cannot be made about the implications of study to these sectors; the enormous variation amongst rangeland types precludes general management recipes. Rangelands differ in management systems varying from nomadic pastoralism through mixed subsistence farming to commercial ranching. As for the pastoral systems, keeping livestock has much to do with culture and security as much with income generation. This makes intervention very complicated. Nevertheless, the research presented here bear relevance mostly to commercial livestock enterprises whose ultimate objective is generally assumed to be the maximum off-take of some livestock

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products especially meat. It is evident that with proper combination of stocking rate and number of paddocks, rotational grazing facilitates efficient use of forage and eventually better gain in individual animal weight (Figure 5.15.). While this is the case, the much anticipated benefits from the rotational grazing systems would largely depend on effective managerial skills besides the type of grazing management procedure. The unprecedented variability of the semi-arid grazing environments requires that management has to be adaptive in response to various situations. Under these circumstances, one recommendation is the introduction of responsive stocking rate strategies based on seasonal climate forecasting and/or according to available forage. The commercial implication of this management option is that animal sales would not be determined by the market demand but climatically dictated; hence, compromising the profitability of the enterprise. On the other hand, a combination of responsive stocking strategy and rotational grazing system implies that forage can be preserved and made available to animals throughout the growing season and sales aligned according to market demand.

6.4 On uncertainty and Sustainability of Semiarid Rangelands

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Uncertainty in semiarid rangelands is one of the essential challenges and the question arises about how to achieve sustainability under uncertainty. The use rotational grazing systems in combination with continuous grazing especially at the beginning of the growing season would reduce the impacts of year to year variability of the production system (Figure 6.4). If sustainability is used as a principle that guides present decisions and actions toward the future, and if the future rainfall is uncertain, rotational grazing systems should be deployed as effective tools. However, Ludwig et al. (1993) argue that large levels of natural variability mask the effects of overexploitation. They strongly emphasize that initial overexploitation is not detectable until it is severe and often irreversible. As such, they caution that future events cannot be predicted, and even well meaning attempts to exploit responsibly may lead to disastrous consequences. Thus, the benefits of using rotational grazing systems are bound to fail when large scale rainfall variability persists over large timescales. As such, other appropriate measures to the use grazing systems will be sought and implemented accordingly. For example, effective policies are possible under severe conditions of uncertainty as advocated by the well-developed theory of decision making under uncertainty (Chernof & Moses, 1959 cited by Ludwig et al., 1993). Since most principles of decision-making under uncertainty are simply common sense (Ludwing et al., 1993), implementation of rotational grazing systems under uncertainty should be treated as such. Rotational grazing systems as presented here must be experimented, monitor results and modify the design according to prevalent conditions.

6.5 Further Research

The study has identified three key areas for future research. To begin with, the field of grazing systems has undoubtedly advanced with enormous empirical work. The need for quantitative reviews with robust techniques such as metal-analysis was proposed (Chapter 2). It was argued that a majority of comprehensive reviews in this area has handled the literature with either semi-quantitative or narrative approaches. These approaches have proved useful in summarizing the state of knowledge about grazing systems by way of counting the number of studies with outcomes in favor of a particular grazing system but at times no conclusive results emerging. Nevertheless, studies to determine the magnitude of differences among the various studies by the use of meta-analysis has not been explored. Unfortunately, the current study could not employ this technique as this was beyond its scope.

Application of the model presented here will be site-specific. It will always require parameter estimation to make relevant to other environments. The sensitivity analyses identified a number of parameters in need of further work to accurately estimate their values. The parameters are mainly those for the diet selection and food intake module (Chapter 4). Moreover, more research would involve development or extension of existing pasture models to simulate rotational and continuous grazing systems with heterogeneous vegetation at very large landscape scale. Besides, the use of fire as a management tool is another interesting area for research, particularly when the long-term dynamics are investigated in semi-arid savannah.

Social economic issues determine the success in adoption of various innovative management initiatives, especially considering a subsistence farmer. Integrated research involving the socio-economic aspects of rotational grazing systems would be an important step towards its adoption especially by non-commercial farmers. For example, studies of cost-benefit analysis to elucidate the financial implications of rotational grazing systems are urgently needed.

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Appendices

A. Main *MatLab* Computer Program Code for the Savannah Model

```
function doty = transf( t, y )            % This function must have two input arguments t and y

global dt rainfall ainfill binfill cinfill astmax bstmax cstmax epan humid mugleaf leafmax thetagl
ksg ksroot thetaro rootmax muroot muculm culmmax thetacu muinfl inflmax thetinf ksinf prefgl
prefde prefold prefcu prefinf prefdcu prefdin amede bmede cmede mecu meinfl medecu medeinf
megl wmax qdmi fdmmat kshoot fm skakel ap bp af bf qp pmax minleaf depcarb kresgro tranco
distance nerw qdm maxbite bbite qf fmax animha decdry decrain frcarb muresc ksr kscu gr start

doty = [1 0 rainfall(ceil(t)) 0 0 zeros(17,1)' 0]';                  % initializing column vector

if doty(3) > 12                 % Infiltration initiates when rainwater is over 12 mm

 doty(4) = binfill.* doty(3) - cinfill.*doty(3).*doty(3) - ainfill;
else
    doty(4) = doty(3);
end

if y(7) > 50                      %% initiation of plant growth when soil moisture in the Bst is over 5o mm
    start = 1;
    gr = 1;
elseif start == 0
             gr = 0;
end
if gr ==1 ;
    doty(5) =  doty(1) + dt;                %%  computes growth days
    doty(2) = doty(5)./7;                  %% growth days
end

if doty(4) >= 0    %inflow into the strata
   drain = doty(4);
   if y(6) + drain > astmax
       doty(6) = astmax - y(6);
   else
       doty(6) = drain;
   end

   drain = drain + y(6) - astmax;
   if drain > 0                                      % infiltration into  is Bst
    if y(7) + drain > bstmax
         doty(7) = bstmax - y(7);
      else
         doty(7) = drain;
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```
   end

      drain = drain + y(7) - bstmax;
      if drain >= 0 %something is draining out of STB
        if y(8) + drain > cstmax
            doty(8) = cstmax - y(8);
        else
            doty(8) = drain;
        end
      end
   end
end

 shoot = y(10)+y(11)+y(12)+y(13)+y(14)+y(15)+y(16);
% Shoot is computed as the sum of all masses of the structures (green leaf etc.

if  shoot <= 0
        pvap = epan./7;
   else
        pvap = (epan./7).*(1-(0.0422 + 0.1537*log(shoot)));
   end

 if y(6) >= 24
        fr = 0.4667.*y(6) - 10.9;
   else
        fr = 0.0375.*y(6) - 0.6;
   end

if fr < 0
       fr = 0;
else
       fr = fr;
 end

evap = fr.*pvap;

if y(10) < 78.118
       k = 0.018 - (1.728e-04 .* y(10));
   else
       k = 0.00483 - (4.2243e-06 .* y(10));
end

pottr = y(10).*(epan/7).*k;
totst = y(6) + y(7) + y(8);
smtrin= (0.043.*totst) - 3.73;

if smtrin > 1
      ktrin = 1;
elseif smtrin < 0
      ktrin = 0;
```

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```
else
     ktrin = smtrin;
 end

   totrans = ktrin .* pottr;

   volast  = y(6) ./ 0.88;
   volbst  = y(7) ./ 2.46;
   volcst  = y(8) ./ 3.54;
   voltst  = volast + volbst + volcst;

   propast = volast ./ voltst;
   propbst = volbst ./ voltst;
   propcst = volcst ./ voltst;

   transa  = propast .* totrans;
   transb  = propbst .* totrans;
   transc  = propcst .* totrans;
   qtrans  = totrans ./ humid;

   if y(5) == 0
        leafgro  = 0; %a singed a value every time
        storc    = 0; %a signed a value every time
        rootgro  = 0; %a signed a value every time
        culmgro  = 0; %a signed a value every time
        inflgro = 0; %asigned a value everytime
   elseif qtrans == 0
        lgrmax   = 0; %local variable used as a register
        leafgro  = 0; %asigned a value every time
        %rcgrmax = 0; %a dud
        storc    = 0; %a signed a value every time
        %rootgmx = 0; local register
        rootgro  = 0;
        culmgmx  = 0; %asinged a value every time, local variable
        culmgro  = 0;
        inflgro  = 0;
   else

        lgrmax  = mugleaf .* y(10).* ( 1 - ((y(10) + y(13)) ./ leafmax).^thetagl);
        leafgro = lgrmax ./ (1 + ksg ./ y(9));
        rootgmx = muroot .* y(18).* (1 - (y(18) ./ rootmax).^thetaro);
        rootgro = rootgmx ./ ( 1+ksroot ./ y(9) );
        rescmax = frcarb .* y(18);
        storc   = muresc .* y(18) .* (rescmax - y(17));
        storc   = storc ./ ( 1 + ksr ./ y(9) );
        if storc <= 0, storc = 0; end

        if y(11) == 0
            culmgmx = 0;
            culmgro = 0;
```

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```
      else
        culmgmx = muculm.*y(11).*(1 - (y(11) ./ culmmax).^thetacu );
        culmgro = culmgmx./( 1 + kscu./y(9) );
      end

      if y(12) == 0
        inflgmx = 0;
        inflgro = 0;
      else
        inflgmx = muinfl.*y(12).*(1 - (y(12)./inflmax).^thetinf);
        inflgro = inflgmx ./ ( 1 + ksinf ./ y(9) );
      end
  end

if shoot <= 20.0

    gldie = 0;

elseif y(2) < 10

    gldie = 0.00171;

          elseif y(2) < 26

    gldie = 0.00011 * y(2) - 0.000286;
else

    gldie = 0.02;
end
  if totst < 110
      acldie = (10.57 - 0.087 .* totst) .* gldie;
  else
      acldie = gldie;
  end

  frgleaf = y(10)./ shoot;
  frdead  = y(13)./ shoot;
  frolde  = y(14)./ shoot;
  frculm  = y(11)./ shoot;
  frinfl  = y(12)./ shoot;
  frdecu  = y(15)./ shoot;
  frdeinf = y(16)./ shoot;
  sumpref = frgleaf .* prefgl + frdead .* prefde + frculm.*prefcu;
  sumpref = sumpref + frolde.*prefde;
  sumpref = sumpref + frinfl.*prefinf + frdecu.*prefdcu +      frdeinf.*prefdin;

  frgldi  = frgleaf.* prefgl ./ sumpref;
  frdedi  = frdead .* prefde ./ sumpref;
  frolddi = frolde .* prefold./ sumpref;
  frcudi  = frculm .* prefcu ./ sumpref;
  frinfdi = frinfl .* prefinf./ sumpref;
```

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```
  frdcudi = frdecu .* prefdcu./ sumpref;
  frdindi = frdeinf.* prefdin./ sumpref;

  if y(5)  == 0
      mede = cmede;
  elseif y(5) < 30
      mede = amede;
  else
      mede = amede - bmede .* (y(5) - 30);
  end

  mediet = megl.*frgldi + mede.*frdedi + mecu.*frcudi;
  mediet = mediet + cmede.*frolddi;
  mediet = mediet + meinfl.*frinfdi + medecu.*frdcudi + medeinf.*frdindi;
  qdiet  = mediet ./18.4;
  xwt    = y(20) ./wmax; %%DEVIATION HERE

  yint   = qdmi .* xwt + ( 1- qdmi).* xwt .* xwt;
  empint = yint .* fdmmat ./ (1 - qdiet ./ 0.82 );
  fedmi  = empint;
  adjdm  = ((shoot./kshoot).^qdm)./(1 + (shoot./kshoot).^qdm);

%    oldarc = arcde;
   arcade = 8.25 .* y(20).^ 0.29 .* wmax .^ 0.07;
   bidmi = maxbite * bbite * arcade * adjdm;

   if fedmi < bidmi
      dmi = fedmi;
   else
      dmi = bidmi;
   end

   ge  = 18.4 .* dmi;
   hb  = fm .* y(20) .^ 0.67;
   g   = ge./hb;
   egm = 0.503 .* qdiet + 0.35 .* qdiet .* qdiet;
   egg = 0.006 .* qdiet + 0.78 .* qdiet .* qdiet;
   bke = egm ./ (egm - egg);

 p   = egm*log(egm ./ egg);

   if skakel == 0   %%{switching between methods of estimating
          composition of gain}
      pcg = ap.*y(20).^bp;
      fcg = af.*y(20).^bf;
   else %%{Butterworth's method for body composition}
      awmax = 1./wmax;
      bwmax = 1./(wmax.*wmax);
      pcg = qp .* pmax.* awmax;
      pcg = pcg + 2* (1-qp)* pmax * bwmax * y(20);
      fcg = qf .* fmax .* awmax;
      fcg = fcg + 2 * (1-qf)* fmax * bwmax *y(20);
   end

   ecg    = 23.6*pcg + 39.3 * fcg;
   grglea = dmi .* frgldi .* animha .* 0.1;
```

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```
    grdead = dmi .* frdedi .* animha .* 0.1;
    grolde = dmi .* frolddi.* animha .* 0.1;
    grcul  = dmi .* frcudi .* animha .* 0.1;
    grinfl = dmi .* frinfdi.* animha .* 0.1;
    grdecu = dmi .* frdcudi.* animha .* 0.1;
    grdeinf= dmi .* frdindi.* animha .* 0.1;

% WE CAN COMMENT OUT HERE TO RUN THE PADDOCK SYSTEM
% computes one paddock  grazing at the end of the season. We can adjust the figures according to the
number of paddocks in the rotational cycle. The example below is a six-paddock system at the stocking
rate of 0.2 steers/ha.

% %      FIRST PADDOCK IN A SIX PADDOCK SYSTEM

%     if ~(y(1) < 365*5/6 || y(1) > 365*6/6)

%       animha = 1.2000;
%
%     else
%   animha = 0.0;
%     end

%% SIMULATING A SECOND PADDOCK IN A SIX-PADDOCK SYSTEM
%     if ~( y(1) < 365*4/6 || y(1) > 365*5/6)

%       animha = 1.2000;
%
%     else
%   animha = 0.0;
%     end

%%  SIMULATING THIRD PADDOCK IN A SIX-PADDOCK SYSTEM

%     if ~( y(1) < 365*3/6 || y(1) > 365*4/6)
%       animha = 1.2000;
%
%     else
%   animha = 0.0;
%     end

% SIMULATING THE FOURTH PADDOCK IN A SIX-PADDOCK SYSTEM

%     if ~( y(1) < 365*2/6 || y(1) > 365*3/6)
%       animha = 1.2000;
%
%     else
%   animha = 0.0;
%     end

   if ( y(5) > 0 ) && ( y(5) < 60 )
       frdec = decrain;
    else
       frdec = decdry;
```

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```
   end

   decdead = frdec .* y(13);
   decolde = frdec .* y(14);
   decculm = frdec .* y(11);
   decinfl = frdec .* y(12);
   decdecu = frdec .* y(15);
   decdein = frdec .* y(16);

 % DIFFERENTIAL EQUATIONS OF STATE VARIABLES

   doty(6) = doty(6) - evap - transa;                    % Depletion of water store in soil horizon A

                      doty(7) = doty(7) - transb;                                                   %
Depletion of water store in soil horizon B

   doty(8) =   doty(8) -transc;                                        % Depletion of water store in
soil horizon C


   if y(5) < 175
       pseff = 1;
    else
       pseff = 2.75 - (0.01 .* y(5));
             end

                       %      { use of root reserves to initiate green leaf growth }
   if gr == 0
      resgro = 0;
   elseif (y(5) < 120) && (y(10) < minleaf)
      resgro = kresgro .* depcarb .* y(17);
   else
      resgro = 0;
   end

%    {Production and utilisation of subsrate}

   if gr == 0
      doty(9) = 0;
   else
      doty(9) = qtrans .* tranco .* pseff - leafgro - rootgro;
   end

   doty(9) = doty(9) - culmgro - inflgro - storc;

%   {growth, death and utilisation  of leaves etc}

   doty(10) = leafgro + resgro - acldie .* y(10) - grglea;

  if ~(y(5) > 98 || y(5) < 100)
```

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```
        doty(11) = 1 -  doty(11) ;

        doty(12) = 1- doty(12) ;        % Dead Leaves

    else
        doty(11) = culmgro - grcul - decculm;

        doty(12) = inflgro - grinfl - decinfl;

    end
    doty(13) = acldie .* y(10) - grdead - decdead;

    doty(14) = -grolde - decolde;


% %    Dead culms and inflorescences
    doty(15) = -grdecu - decdecu;

    doty(16) = -grdeinf - decdein;
%
%    If ResGRO = 0 then  {accretion & depletion of stored reserves}

    if ( y(5) < 120 ) && ( y(10) < minleaf )
        resdep = depcarb .* y(17);
    else
        resdep = 0;
    end

    doty(17) = storc - resdep;

    doty(18) = rootgro - 0.0025 .* y(18);   % {Growth and death of roots}

    newalk = nerw .* distance .* y(20) ./ 1.0E06;
        doty(19) = hb .* (bke .* (1-exp(-p.*g))-1) - newalk;
        doty(20) = doty(19) ./ ecg;

    doty(21) = dmi.*animha;

    %%ADJUSTEMETS
    if doty(20) > 0, doty(23) = doty(20); end
```

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B. Function for Parameters and Initial Conditions

```
function [ tout, yout] = graze(T)   % need input T as period for which the simulation runs

global dt rainfall ainfill binfill cinfill astmax bstmax cstmax epan drain humid mugleaf leafmax
thetagl ksg ksroot thetaro rootmax muroot frcarb muresc ksr muculm culmmax thetacu muinfl
inflmax thetinf ksinf prefgl prefde prefold prefcu prefinf prefdcu prefdin amede bmede cmede mecu
meinfl medecu medeinf megl wmax qdmi fdmmat kshoot qdm fm skakel ap bp af bf qp pmax
animha minleaf depcarb kresgro tranco distance nerw maxbite bbite qf fmax decdry decrain kscu gr
start grred drydie

 dt     = 0.1;                  % integration step
 drydie = 0.02;                 % constant for the death of plant   material

 rainfall = rainfall80;    % Rainfall file for the 1980 data set. figure 80 can be change call other
                                rainfall data sets e.g. Rainfall
                                % for   1977 can be written as rainfall = rainfall77

ainfill = 0.4;                  % parameter for water infiltration in  soil horizon A

binfill = 1.05;                 %% parameter for water infiltration in soil horizon B

cinfill = 0.0054;               %% parameter for water infiltration in soil horizon

astmax   =  25.500;             %% maximum water holding capacity for stored water in A horizon

 bstmax   =  71.500;            %% maximum water holding capacity for stored water in Horizon B
cstmax   = 102.5;               %% maximum water holding capacity for  stored water in Horizon C
epan     = 70.0;              % pan evaporation
drain    = 0;
humid    = 50;                %  humidity constant


% Parameter for green leaf and root production module

mugleaf  = 9.4565800E-0002;       % green leaf growth rate parameter
leafmax  = 450.0000;              % potential maximum green leaf biomass (g m-2)
thetagl  = 1;                     % shape parameter
ksg      = 2.250000;              % parameters for root growth

% Root (see parameter interpretation in the text (Chapter 3)
ksroot   = 35.00000;
thetaro  = 1.000000;
rootmax  = 1800.000;
muroot   = 0.4206000;

% Carbohydrate reserves (parameter interpretation in the text Chapter 3)

frcarb   = 3.000000E-0002;
muresc   = 1.000000E-0003;
ksr      = 70.00000;                % Parameters for culms and inflorescences

% Culms (see parameter interpretation in the text (Chapter 3))

  muculm   = 1.000000;
  culmmax  = 80.00000;
```

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```
  thetacu  = 1.000000;

% Inflorescences
  muinfl   = 1;
  inflmax  = 40.00000;
  thetinf  = 1.000000;
  ksinf    = 15.00000;

% feed preferences for various plant components
    prefgl   = 10.000000;
    prefde   = 1.000000;
    prefold  = 0.9000000;
    prefcu   = 0.7500000;
    prefinf  = 0.7500000;
    prefdcu  = 0.5000000;
    prefdin  = 0.5000000;

    amede    = 8.500000;
    bmede    = 7.500000E-0003;
    cmede    = 7.750000;
    mecu     = 6.000000;
    meinfl   = 6.000000;
    medecu   = 5.000000;
    medeinf  = 5.000000;
    megl     = 9.800000;

% parmeters for animal module
    wmax     = 650.0000;   % measured in kg
    qdmi     = 3.000000;
    fdmmat   = 3.038000;
    kshoot   = 120.0000;
    qdm      = 3.000000;
    fm       = 0.5400000;
    skakel   = 1.000000;
    ap       = 0.2780000;
    bp       = -0.1107000;
    af       = 3.939000E-0003;
    bf       = 0.7880000;
    qp       = 1.110000;
    pmax     = 140.2500;

%     animha   = 0.0010000;  % stocking rate (variable parameter)
    minleaf  = 60.00000;  %  minimum
    depcarb  = 0.100000;
    kresgro  = 0.6666700;
    tranco   = 140.0000;
    distance = 5000.000;
    nerw     = 1.600000;
    maxbite  = 38.00000;
    bbite    = 4.580000E-0003;
    qf       = 0.2100000;
    fmax     = 286.2000;
    decdry   = 1.000000E-0003; % fraction of decay of plant material in the dry season
    decrain  = 2.000000E-0003;% fraction of decay of plant material in the dry season
    kscu     = 15.00000;
    gr       = 0;   % growth switch when water in the B horizon is just 50mm
    start    = 0;  % growth switch when water in the B horizon is just 50mm
```

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```
 % INITIAL VALUES OF VARIABLES

   DAYS    = 1;              %        y(1)-  days
   GRWEEKS = 0;              %        y(2)- growth days
   RAINtot = 0;              %        y(3)- cumulative rainfall
   INFILtot= 0;              %        y(4)- total infiltration
   GRDAYS  = 0;              %        y(5)- growth days

  % Initial water stores (all in mm)

   AST = 10.50000;                   %        y(6) - initial water store in horizon A
   BST = 29.50000;                   %        y(7)  - initial water store in horizon B
   CST = 42.50000;                   %        y(8)  - initial water store in horizon C

% Initial plant variables (all are measured in g m-2)

   SUBSTR=10.000000              ;%        y(9)  -   initial substrate quantity
   GLEAF= 0.000000;                %         y(10) – initial green leaf biomass at the start of the
season                                                 is zero
   CULM = 0.000000;                %        y(11) – culms appear later in the season
   INFLOR = 0.000000;              %        y(12)  - inflorescence are initially zero and appear later
   DEADLEA = 15.000000           ;%         y(13)   - initial dead leaf carried on from previous season
   OLDEADL = 70.00000;             %        y(14)    - old dead leaf biomass is initially the most
                                                                 abundant
   Deadcu  = 15.00000;             %        y(15) – dead culms biomass
   DeadInf = 20.000000;            %        y(16)   - dead inflorescences biomass
   RESCARB = 30.00000;              %       y(17) –  carbohydrate reserves


 % Intial animal variables

   BENERGY = 1946.000; % y(19) – balance energy (specified in the text)
   WEIGHT  = 250.0000000; %y(20) – individual animal weight (kg)
   TotDMI  = 0.000000;  %y(21)- total dry matter intake (kg)


   F       = [AST BST CST SUBSTR GLEAF CULM INFLOR DEADLEA OLDEADL Deadcu
DeadInf RESCARB ROOT BENERGY WEIGHT TotDMI MortR];
   xwt     = 0; %23

  if nargin < 1, error('not enough input terms'); end

   if nargin < 2, yo = [DAYS GRWEEKS RAINtot INFILtot GRDAYS  F xwt]'; end;
   options = odeset('RelTol',1e-6,'AbsTol',1e-6, 'NonNegative', (1:23));
   [ tout, yout ] = ode15s( @transf, T, yo, options );

% ODE15s solve stiff differential equations
```

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C. Rainfall Data Sets Used In Simulation

1979/1980				1980/1981		1976/1977				1978/1979	
Day	Rainfall (mm)	Day	Rainfall (mm)	Day	Rainfall (mm)	Day	Rainfall (mm)	Day	Rainfall (mm)	Day	Rainfall (mm)
15	3.4	141	13.7	31	27	22	8.3	129	4.60	43	3.0
48	1.0	142	11.1	55	5.3	23	0.8	130	0.20	44	11.5
52	0.6	143	53.6	57	9.0	24	0.7	132	4.10	45	0.3
54	4.9	147	5.2	58	6.5	26	10.4	133	0.80	51	0.5
6	13.9	148	3.4	78	5.9	27	5.2	134	18.70	54	0.5
70	17.3	150	27.8	82	36.5	49	2.2	135	4.00	55	2.0
73	3.5	151	21.7	83	11.5	50	77.5	140	1.80	67	1.1
80	8.5	154	26.0	84	11.5	63	3	142	1.00	74	27.0
82	47.5	155	30.4	86	9.5	64	2.6	143	1.50	75	17.4
83	9.4	157	10.7	87	39.7	72	8.2	145	1.30	76	0.6
84	31.1	158	34.9	90	11.5	75	0.6	146	96.40	79	0.5
85	0.4	159	2.8	108	2.7	82	1.4	148	35.40	81	5.0
86	65.4	161	11.7	109	3.9	83	5.5	149	11.20	82	0.2
87	6.5	162	5.2	113	26.7	88	1.4	150	2.70	85	1.0
88	3.7	165	1.2	115	0.6	90	19.4	151	6.00	91	25.4
89	15.1	171	1.5	116	1.8	91	27.7	152	12.50	96	3.9
103	2.1	180	2.1	124	19.5	93	0.2	156	25.80	99	4.3
104	10.0	184	4.4	125	21.7	94	29.1	157	6.50	101	33.6
105	45.5	196	3.2	126	42.2	95	12.5	158	5.50	109	19.3
107	7.0	208	3.0	127	2.7	104	27.1	161	5.70	110	0.7
108	0.3	209	26.1	138	0.6	105	0.8	164	4.10	116	0.5
112	0.5	235	2.1	164	2.8	106	14.6	165	14.00	125	7.1
115	11.1	238	18.5	171	3.3	107	16	166	1.80	131	19.9
120	1.2	245	1.0	172	17.5	108	16.5	167	1.70	134	8.1
125	8.1	257	0.6	177	10.1	109	14.7	168	33.00	135	2.3
127	31.7	259	2.6	185	31.2	110	15.4	169	6.10	153	5.8
128	24.0	260	2.9	204	1.8	111	2	170	34.80	154	5.3
129	2.9	261	3.3	224	7.5	112	76	171	0.40	156	2.0
130	4.0	265	3.5	226	7.1	113	10.4	172	8.50	157	1.8
131	6.5			229	2.7	114	40.1	174	23.90	161	0.9
132	1.1			242	3.5	115	11.6	175	3.00	172	2.0
133	3.2			244	8.0	116	5.8	176	0.40	173	13.6
135	27.2					120	7.7	183	0.30	203	1.1
						121	4.1	184	15.90	204	11.6
						122	6.7	185	4.90	205	23.6
						123	15.2	186	0.50	206	6.5
						124	1.7	187	0.50	212	0.5
						126	9.7	188	0.30	213	43.8
						127	0.6	190	24.10	214	16.0
						128	19	191	1.00	275	0.6
								195	2.30	297	3.1
								201	0.70	310	4.5
								214	0.70		
								231	37.70		
								232	61.50		
								265	0.30		
								266	11.10		
								267	0.40		
								280	0.80		
								283	0.80		
								346	16.90		

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D. Parameter Values and Unit of Measure. Those without units are indicated as n/a.

Module	**Parameter**	**Interpretation**	**Value**	**Units**
SOIL-WATER BALANCE				
	W_{Astmax},	Maximum water store A	25.5	mm
	W_{Bstmax}	Maximum water store B	71.5	mm
	W_{Cstmax}	Maximum water store C	102.5	mm
	E_{pan}	Maximum rate of evaporation	70.0	mm
	Humid	Actual humidity		g cm^{-3}
	ϕ_{smi}	Variable parameter of soil moisture index	n/a	n/a
PLANT GROWTH	$G_{gl,\ max}$	Maximum green leaf biomass	450.0	g m^{-2}
	θ_{gl}	Shape parameter for green leaf	1.00	n/a
	θ_{r}	Shape parameter for root	1.00	n/a
	$\theta_{\inf}$	Shape parameter for inflorescence	1.00	n/a
	θ_{cu}	Shape parameter for culms	1.00	n/a
	μ_{gl}	Fractional rate of growth of green leaf	0.099418	day^{-1}
	μ_{Cu}	Fractional rate of growth of green leaf	1.00	day^{-1}
	$\mu_{\inf}$	Fractional rate of growth of	1.00	day^{-1}
	μ_{r}	Fractional rate of growth of inflorescence	1.00	day^{-1}
	$G_{gl,\ Ksu}$	Michaelis-Menten constant for green leaf substrate	2.25	n/a
	$G_{inf,\ Ksu}$	Michaelis-Menten constant for inflorescence substrate	15.00	n/a
	$G_{cu,\ Ksu}$	Michaelis-Menten constant for culm substrate	15.00	n/a
	Depcarb	Parameter for deposition of carbohydrates reserves	0.10	n/a
	$G_{r,\ Ksu}$	Michaelis constant for root substrate	70.00	n/a
	kresgro	Michaelis constant for production of carbohydrates	0.66667	n/a
	tranco	Transpiration coefficient	140.00	n/a

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	Dec_{dry}	Dry season fractional rate of decay of plant materials	0.001	day^{-1}
	Dec_{rain}	Rainy season fractional rate of decay of plant materials	0.02	day^{-1}
DIET SELECTION AND FOOD INTAKE	W_{mat}	Mature weight of cattle	250.0	kg
	Qf	Parameter of fecal output	0.210	Kg
	fmax	Maximum fat content	286.2	Kg
	$bite_{max}$	Maximum bite per day	0.00458	Kg
	D_{walk}	Distance walked	5000.0	M
	W_{max}	Maximum weight of cattle	650.0	Kg
	Qmi			
	fdm_{mat}	Parameter for digestibility equation	3.038	n/a
	Fm	Parameter Fasting metabolism equation		MJ/kgWd$^{0.75}$
	G_{kshoot}	Parameter of intake adjustment	120.0	Kg/bite
	$bite_{co}$	Potential cow bite size		kg/bite
	Arcade	Variable parameter for mouth size	adjustable	mm
	ap	Coefficient parameter for protein content of gain	0.278	n/a
	bp	Shape parameter for protein content of gain	-0.1107	n/a
	af	Coefficient parameter for fat content of gain	0.003939	n/a
	bf	shape parameter for fat content of gain	0.788	n/a
	Qp	Coefficient parameter for body composition equation	1.11	n/a
	animha	Variable parameter for stocking rate	Adjustable	Steers/ha
	p_{max}	Maximum protein content of gain	140.25	Kg
	qdm	Shape parameter adjustment of dry matter intake		n/a
	Qdmi	Dry matter intake parameter	3.0	Kg/bite
	Qdm	Parameter for adjustment of dry matter intake	3.0	Kg/bite
	qf	Coefficient parameter for body fat equation	0.21	n/a
	Φ_{walk}	A parameter for energy expenditure for a unit distance		kj/m

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