HELMHOLTZ
CENTRE FOR
ENVIRONMENTAL
RESEARCH – UFZ

PhD Dissertation 14/2011

Risk management in semi-arid rangelands: Modelling adaptation to spatio-temporal heterogeneities

Oliver Jakoby

ISSN 1860-0387

Risk management in semi-arid rangelands: Modelling adaptation to spatio-temporal heterogeneities

Dissertation zur Erlangung des Doktorgrades der Naturwissenschaften (Dr. rer. nat.)
am Fachbereich Mathematik und Informatik der Universität Osnabrück

vorgelegt von
Dipl.-Biol. Oliver Jakoby
aus Frankfurt am Main

Osnabrück 2011

"Es dauert meist sehr lange bis man in Farmerkreisen zu der Einsicht kommt, daß der erfolgreichste Farmer nicht derjenige ist, der nur sein Vieh sorgfältig betreut, sondern derjenige, der seine Aufmerksamkeit sowohl dem Vieh als auch der Pflanzendecke schenkt. [...] Denn die Weide ist die Grundlage der Tiererhaltung; sie ist das Kapital des Farmers und die Voraussetzung für seinen Lebensunterhalt. [...] Man kann auf Dauer nur von den Zinsen des Kapitals leben, also vom Zuwachs der Weide, und darf das Kapital selbst nicht angreifen, sonst ist es eines schönen Tages dahin."

Heinrich Walter (1954)
aus: Grundlagen der Weidewirtschaft in Südwestafrika

Abstract

Livestock grazing is the most important type of land-use in arid and semi-arid regions. In these regions, uncertain and highly variable climate conditions cause scarce and spatio-temporally variable resource availability. The major challenge to livestock grazing is the efficient utilisation of these resources without running the risk of degradation. Therefore, well adapted grazing strategies that consider both local environmental characteristics and the farmers' individual needs and perceptions are crucial for sustaining human livelihoods. Particularly, rotational grazing is presumed to render adaptation to spatio-temporal heterogeneities possible. A systematic investigation, however, that analyses the interrelations between the major components of rotational grazing systems on appropriate spatial and temporal scales was missing so far.

This doctoral thesis investigates different management strategies for sustainable livestock grazing in semi-arid rangelands. Using an integrated modelling approach, it enters into the question: how to adapt grazing systems to spatio-temporal heterogeneous rangeland conditions, variable and changing climate conditions, and different individual needs and goals of livestock farmers?

In order to address these issues, the taken approach tackles both methodical challenges and applied concerns. In the first part of this study, a generic modelling framework is developed that incorporates important components of grazing systems on appropriate spatial and temporal scales. To parameterise the model, a pattern-oriented approach is developed that uses qualitative patterns to derive a broad range of plausible parameter sets supporting a general model analysis.

In the second part, a variety of management strategies is explored under different climatic, ecological, and economic conditions. The research focuses in particular on combined effects between and relative importance of different management components. The question how the results of different management strategies depend on the type of vegetation is investigated. Furthermore, the performance of rotational grazing strategies is analysed under different economic requirements and rainfall conditions. The study also identifies management strategies that are suitable to adapt a grazing system to spatio-temporally variable rangeland conditions.

Overall, this thesis contributes to a general understanding of basic principles for adaptation to spatio-temporal heterogeneities as well as the interplay of different management components. The results allow an evaluation of management strategies for specific situations and the identification of strategies that are robust to a broad range of situations including different aspects of global change.

Contents

Chapter 1

Introduction

1.1 General introduction

Managed grazing systems cover more of the earth's surface than any other form of land use (Asner *et al.*, 2004; WRI, 2000). Also, livestock production contributes 40 percent of the global value of agriculture output and supports the livelihood of almost a billion people (FAO, 2009). Moreover, it is one of the fastest-growing agricultural subsectors in developing countries and is expected to continue growing strongly (Bruinsma, 2003; Delgado *et al.*, 1999). This poses the risk of overutilisation and land degradation and implies great challenges in terms of efficient as well as sustainable use of natural resources. Most likely, this aggravates under global change. Therefore, well-adapted management strategies are essential to support the accelerating needs while still ensuring viable land-use.

Approximately 50 percent of the world's livestock is supported by range in drylands (Millennium Ecosystem Assessment, 2005a). Thereby, the greatest extend lies in semi-arid regions (Fig. 1.1), where ecosystems and populations are probably the most vulnerable to loss of ecosystem services. Strong indications for long-term degradation are found already for semi-arid and arid rangelands all over the world (e.g. Dregne, 2002; UNEP, 1997; Dean and Macdonald, 1994; Helldén, 1991; van Keulen and Breman, 1990; Schlesinger *et al.*, 1990). Already 10 − 20 percent of all grassland is degraded to some extent (Millennium Ecosystem Assessment, 2005a). This degradation is largely caused by overuse and range mismanagement, and in turn, expected to lead to a decline in livestock numbers.

Under consequences of global change these problems are expected to increase (Asner *et al.*, 2004). It is likely that some of the greatest impacts of climate change will be felt in grazing systems in arid and semi-arid areas (Hoffman and Vogel, 2008). With a high degree of certainty climate change, land use developments, and land cover changes will lead to an accelerated decline in water availability and biological production (Millennium Ecosystem Assessment, 2005a). Particularly, reduced rainfall and increased frequency of drought will reduce primary productivity of rangelands, leading to overgrazing and degradation, which may result in food insecurity (FAO, 2009).

The threatening risk of degradation in combination with the increasing demand of livestock production reveals the need for viable land-use strategies that increase

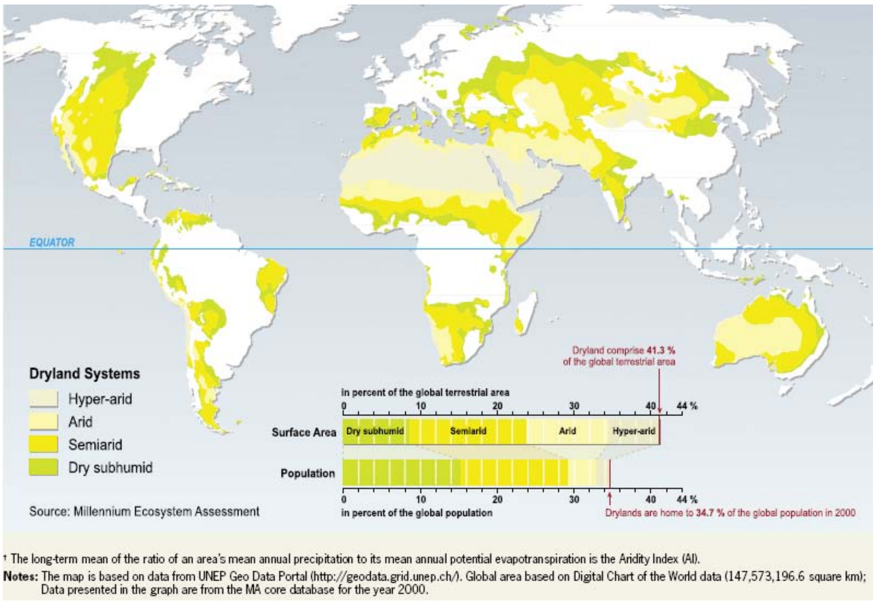


Figure 1.1: Global map of dryland areas. Drylands include all terrestrial regions where the production of crops, forage, wood and other ecosystem services are limited by water. (Source: Millennium Ecosystem Assessment, 2005b).

the yield of rangelands while coevally ensuring the long-term ecological as well as economic sustainability, in particular under climate change. Such strategies must suite the characteristics of the local environment, economic and social factors as well as individual aims and values (Sandford, 1982). Especially, the ecological and the economic component of semi-arid rangelands are tightly coupled (e.g. Frank *et al.*, 2006; Janssen *et al.*, 2004; Heady, 1999; Perrings, 1997): the vegetation biomass is directly used as forage for livestock, which is the main source of income. In turn the grazing pressure directly influences the vegetation dynamics.

Grazing management is the crucial link that controls this feedback between the ecological and the economic system. The management must cope with rather low, spatio-temporally heterogeneous primary production that is essentially driven by a low and highly variable precipitation (Sullivan and Rhode, 2002; Behnke *et al.*, 1993; Westoby *et al.*, 1989). Therefore, the intensification of pastures is frequently unprofitable or technically unfeasible (Millennium Ecosystem Assessment, 2005a). Hence, extensive livestock farming is the major form of land utilisation. Mainly two types of pastoral livestock management can be distinguished: traditional and commercial pastoralism (Beaumont, 1993). While traditional strategies typically use large-scale movement to cope with the heterogeneous environmental conditions, commercial rangelands are bounded to comparatively small private properties (Reid *et al.*, 2007). Farm borders restrict long-range livestock movements (Coughenour, 1991; Walker *et al.*, 1981), and therefore, shorten or eliminate vegetation recovery periods previously allowed by traditional systems (Hudak, 1999; Coughenour, 1991). To overcome this problem, various local management schemes developed and particularly rotational grazing was designed to incorporate spatial aspects (Kothmann, 2009; Tainton, 1999; Heady and Child, 1994; Heitschmidt and Taylor, 1991). Such rotational schemes subdivide the rangeland and graze pastures in a rotational sequence to allow recovery of rested areas. In this regard, timing and spatial distribution of grazing as well as stocking rate are important variables to improve the management system (Walker, 1995). Different forms of rotational grazing emerged (Holechek, 1983), including deferred-rotation grazing (Merrill, 1954), rest rotation grazing (Hormay, 1970), high intensity - low frequency grazing (Acocks, 1966), or short-duration grazing (Savory and Butterfield, 1998; Savory and Parsons, 1980). However, the optimal arrangement is still heavily discussed (Brown and Kothmann, 2009; Holechek *et al.*, 1999a; Heitschmidt and Walker, 1983), and in a recent literature review, Briske *et al.* (2008) challenge the empirical evidence for the benefits of rotational grazing in general. Also, the best stocking strategy that manipulates the total amount of livestock over time is strongly debated (Campbell *et al.*, 2006; Sandford and Scoones, 2006; Illius *et al.*, 1998; Behnke *et al.*, 1993; Westoby *et al.*, 1989). However, there is an urgent need of sustainable strategies that reduce the vulnerability of livestock production systems in semi-arid rangelands. But what characterises such sustainable management systems?

Altogether, there are plenty of different management approaches and tools available in the praxis. However, there seems to be no agreement neither which are generally recommendable, nor how they differ under various conditions that are present in drylands. Especially, in such coupled human-environmental systems where interactions are manifold and complex (Reynolds *et al.*, 2007; Liu *et al.*, 2007) it is difficult to find one general optimal strategy. Strategies must suite individual needs, goals and abilities of farmers and account for local environmental conditions. Therefore, individually suitable strategies might differ in their degrees of complexity and adaptivity. To avoid mismanagement and overgrazing, management strategies have to be suitably adapted to the spatio-temporal variability of natural resources and should be robust even under adverse consequences of climate change. At large, numerous factors play a role to achieve sustainable management (Weltz *et al.*, 2003; Walker and Abel, 2002; Hoekstra and Joyce, 1999). Therefore, a better understanding of processes and relations between ecological, climatological, and socio-economic factors is needed (Asner *et al.*, 2004) to derive general principles for management of semi-arid rangeland. Such general principles of well-adapted and robust management strategies are needed to assist individual decision support and policy-making.

1.2 Management components of grazing systems

The diversity of management strategies on commercial livestock farms that are supposed to improve rangeland utilisation is manifold. They differ particularly in their complexity and their degree of adaptivity. For example, the stocking component of a strategy, which is known as most important variable of the management system (Batabyal *et al.*, 2001; Holechek, 1988), can either stay constant for a long time span or constantly be adapted to track temporal environmental variability. In the same way, the rotation rules that coordinate the spatio-temporal utilisation of the rangeland show different alternative arrangements that strongly depend on the infrastructure on a farm. The chosen infrastructure limits the range of management possibilities. Here, mainly the number and size of fenced pastures as well as the location of water posts are crucial variables. They determine the ability to utilise certain areas of the rangeland while giving rest to others. Additionally, the spatial distribution of the livestock impacts the rangeland quality and therewith, the long-term performance of a grazing system. Furthermore, the standing time in combination with the size of a pasture determines the local grazing pressure. Thereby, a long standing time will give great pressure to the grazed pasture while allowing a long recovery time for all other pastures. Than again, a short standing time produces only low local pressure, but reduces the resting period of other pastures. Also, the rotation rule influences the utilisation pattern by determining which pasture is grazed next. Likewise, this can shorten or extend resting periods of single pastures. Overall, this results in a great variety of possible strategies ranging from a continuous grazing on one single pasture with a constant number of livestock to a highly subdivided farm with a sophisticated rotation and stocking system that requires permanent observation of the pasture status to derive management decisions.

1.3 Research questions

As outlined above, livestock production in drylands is threatened by a multitude of different factors. To meet those challenges plenty management approaches are available and adopted in practice. However, interactions between the ecological and the management system are diverse and complex (Hodgson and Da Silva, 2000). Furthermore, they are related across several temporal and spatial scales (Stuth and Maraschin, 2000). Therefore, in order to ensure sustainability, it is vitally important to know which strategies sufficiently adapt management systems to spatio-temporal heterogeneities of rangeland conditions, variable and changing climate conditions, and different individual needs and goals of livestock farmers.

In this regard, several modelling studies already focused on different components of rangeland management, including stocking rate (Sandford and Scoones, 2006; Campbell *et al.*, 2000; Illius and O'Connor, 1999), rangeland infrastructure (Beukes *et al.*, 2002), spatial distribution of grazing (Müller *et al.*, 2007; Adler *et al.*, 2001; Weber *et al.*, 2000; Basset *et al.*, 1997; Jeltsch *et al.*, 1997), and ecological-economic aspects (McAllister *et al.*, 2009; Popp *et al.*, 2009; Teague *et al.*, 2009; Higgins *et al.*, 2007; Quaas *et al.*, 2007; Perrings, 1994). However, there is still a lack of generic studies that explicitly analyse consequences of spatial and temporal variability on the management on small scales (Teague *et al.*, 2009; Beukes *et al.*, 2002; Ash and Stafford Smith, 1996; Noy-Meir, 1981). Combined effects between and relative importance of different management components are not directly obvious. Especially, a general systematic analysis that investigates the interplay between different rotation and stocking components will be essential to generate better understanding of rotational grazing approaches.

Therefore, this thesis focuses on management strategies for commercial rangelands in semi-arid regions that consider different spatial and temporal scales. It investigates several possible management strategies to broaden the understanding of sustainable land-use options. For this purpose, those variables of the management system are analysed that manipulate livestock numbers (stocking rate), as well as timing and spatial distribution of grazing patterns (i.e. arrangement of and rotation on fenced pastures). The approach taken in this study investigates different combinations of the following variables: (i) stocking rule (constant vs. adaptive), (ii) stocking rate (grazing pressure on the farm), (iii) number and size of fenced pastured, (iv) rotation rules (which pasture is grazed at which time), and (v) standing time per pasture. The outcome is evaluated regarding different economic objectives that (a) aim at maximum yield, (b) balance mean-variance preference, or (c) take a safety-first approach. Certain strategies are investigated in a stable, and respectively, an uncertain environment that is characterised by different precipitation scenarios.

In the course of this thesis, we tackle questions on different levels of the ecological-economic system. These levels concern some of the most important components of semi-arid grazing systems (i.e. environment, vegetation, rangeland management and management evaluation):

- *Management strategies*: We investigate how different management strategies impact the performance of ecological criteria of the rangeland and how this feeds back on economic criteria. Particularly, we analyse functioning of different management components, their interrelation, and to which system properties they should be adapted to improve grazing management.
- *Vegetation types*: We consider different vegetation types to study which vegetation characteristics determine the kind of rangeland response to a certain management strategy.
- *Climate conditions*: We compares different precipitation scenarios. More precisely, impact of uncertain as well as stable precipitation, and robustness of management strategies under different scenarios of climate change are evaluated.

- *Socio-economic objectives*: We focus on different kinds of economic evaluation of grazing strategies and analyse how different assessment criteria affect the range of suitable management options.

Therewith, we approach mechanistic understanding of the underlying processes. We analyse the different levels to project the consequences of management actions and propose simple rules-of-thumb to initiate further discussion.

1.4 Modelling as a tool for analysing grazing systems

This study uses generic simulation modelling in order to analyse the impact of different system components on the performance of management strategies. Models are frequently used to analyse coupled socio-ecological systems (Carpenter *et al.*, 2009), and already proofed their usefulness for management questions in dryland grazing systems (Jeltsch *et al.*, 2001; Wissel *et al.*, 1996). They are valuable tools to investigate the relationships between key factors to understand the functioning of the system and illustrate options and scenarios in terms of alternative future states facilitating decision-support (Baumgärtner *et al.*, 2008). Particularly, modelling allows conducting virtual experiments that could not be accomplished in field studies, because this would be too costly and time demanding. Also, the results of field experiments would strongly depend on the local environmental conditions that are impossible to synchronise for all arrangements.

In order to investigate in particular rotational grazing systems properly, the model must meet some important demands. First of all, it has to implement a feedback between grazing management and rangeland condition. The changes in the rangeland condition are driven by low and highly variable precipitation and livestock grazing that are known as major drivers of vegetation dynamics in semi-arid regions (Wessels *et al.*, 2007; Fuhlendorf *et al.*, 2001; Fynn and O'Connor, 2000; Skarpe, 1992; Le Houérou *et al.*, 1988; Huntley and Walker, 1982). The management actions taken by a farmer can adapt to these changes. This again, will change the grazing patterns on the rangeland and in turn the rangeland condition. Several management decisions and actions are taken intra-annually. Therefore, the model must represent spatial heterogeneity and intra-annual temporal variability of semi-arid rangelands (Laca, 2009; Vetter, 2005). In this regard, spatio-temporal heterogeneity of grazing in terms of timing and location of defoliation must be incorporated to investigate the optimal timing of grazing periods.

Several modelling studies have already investigated grazing management questions in drylands (see Wiegand *et al.*, 2008; Tietjen and Jeltsch, 2007, for an overview) and intended general understanding. However, many of them neglected intra-annual processes and interactions (e.g. Popp *et al.*, 2009; Müller *et al.*, 2007; Beukes *et al.*, 2002; Weber *et al.*, 2000; Jeltsch *et al.*, 1997), spatial heterogeneity (e.g. Higgins *et al.*, 2007; Illius and O'Connor, 2000; Illius *et al.*, 1998; Noy-Meir, 1978), or did not take account of both (e.g. Quaas *et al.*, 2007; Janssen *et al.*, 2004; Anderies *et al.*, 2002; Campbell *et al.*, 2000). This thesis emphasizes and combines these two aspects of grazing management in drylands. Hence, our approach focuses on intra-annual vegetation dynamics and spatial heterogeneity of pasture conditions. This allows a detailed analysis of rotational grazing strategies, a common but heavily discussed management type in semi-arid rangelands (Brown and Kothmann, 2009; Briske *et al.*, 2008; O'Reagain and Turner, 1992). Therefore, our generic model comprises a high spatial and temporal resolution. Weekly time steps and a spatially explicit resolution of single parts of a pasture enable the simulation of intra-annual processes and interactions of vegetation and grazing, and render the in-depth analysis of spatial effects in grazing management possible. To account for the coupled human-ecosystem dynamics the model consists of a vegetation and a management component, and is evaluated for economic criteria.

The development of the generic model in this thesis raises two methodical issues: on the one hand, the model requirements pose the challenge of incorporating details of spatial and temporal rangeland dynamics (i.e. in vegetation and management) while aiming at general insights and broad understanding. The question arises, what the right degree of complexity for a generic as well as intra-annual and spatially explicit representation of a rangeland system is. On the other hand, there is a lack of established parameterisation strategies for generic models. There is no approved method available to detect the range of biological realistic parameter sets of generic models to facilitate general system analysis without analysing the whole range of parameters.

1.5 Structure of this thesis

The thesis is structured in two main parts: first, a methodical part (chapter 2 – 3.2) gives the model description and presents a new approach of pattern-oriented parameterisation for generic models. The second part (chapter 3.3 – 5) regards applied contents and investigates different management strategies for livestock farms in semi-arid regions. The paragraphs that follow briefly introduce the purpose of each chapter and summarise its main research questions.

Chapter 2 describes the generic rangeland model used in this thesis. As focal points this model implements an intra-annual time scale and a local spatial scale of single grazing patches. The model consists of an ecological and a management submodule. The ecological submodule describes the local vegetation dynamics on a rangeland in terms of different components of a perennial plant type. The management submodule is a spatially explicit representation of a livestock farm. Different management options that are investigated in the course of this thesis are implemented.

In chapter 3 a novel method for parameterising generic models is proposed. The chapter comprises a methodical section (3.2), that describes the approach, and an applied section (3.3) that utilise the method for an example of stocking management in semi-arid grasslands. First, the rangeland model is parameterised and the model behaviour of the resulting parameter sets is analysed. To this end, we propose a pattern-oriented approach (Grimm *et al.*, 2005; Wiegand *et al.*, 2003; Grimm *et al.*, 1996) that uses qualitative patterns to describe general functional relations and thresholds of the investigated system. By using these patterns, we filter the whole parameter space to extract biologically realistic areas. The applied section demonstrates the benefits of the proposed approach for the question whether a constant or adaptive stocking strategy is beneficial (e.g. Campbell *et al.*, 2006; Sandford and Scoones, 2006) and how this depends on different model parameters. Finally, the pattern-oriented parameterisation is compared to a random sampling approach, which comprises the whole parameter space.

The next chapters focus on spatial effects in grazing management and investigate different elements of rotational grazing strategies. Chapter 4 studies different approaches of evaluating management strategies in regard to two possible management objectives of livestock farmers: (i) a risk-averse, utility maximizing approach and (ii) a safety first approach. We analyse how the management objective affects the suitability of the management strategy and how this is influenced by climatic variability. To this end, we compare continuous grazing on one single pasture to various strategies of rotational grazing that differ in amount of fenced pastures and standing time. Furthermore, different intensities of adaptive stocking are investigated. Finally, the robustness of the strategies is tested under different scenarios of climate change, i.e. lower mean and higher variance in precipitation.

The purpose of chapter 5 is a detailed analysis of interactions between rangeland condition and management option. We tackle the question, which strategies adapt a rotational grazing system best to spatial and temporal heterogeneous resource availability in order to increase the generated yield. The chapter investigates how different types of adaptability affect the suitability of a management option. To this end, we focus on different rules for stocking and rotation. Particularly, we compare constant livestock numbers with a stocking rule that annually adapts the number of livestock to available forage. Additionally, different rules of livestock rotation among fenced pastures are investigated. These rules differ in the way how the grazed pastures are selected by adapting to different elements of semi-arid rangeland systems, like seasonality, or the local availability of different vegetation components. All management settings are analysed under different degrees of stochasticity to test their vulnerability under different climatic variabilities.

The last chapter (6) reviews the methodical approach of developing and parameterising the rangeland model and summarises the main findings of this thesis. Finally, it gives an outlook to potential directions of further research.

Chapter 2

Simulation model

2.1 General model outline

In order to investigate rotational grazing systems in semi-arid rangelands we build a generic ecological-economic simulation model. The model structure meets the basic structural conditions and feedbacks of semi-arid grazing systems (Fig. 2.1). Important components are abiotic environment (in particular precipitation), vegetation, livestock and management of a farmer. The vegetation dynamics is essentially driven by low and highly variable precipitation (Scoones, 1994; Westoby *et al.*, 1989). Within certain boundaries an increase in the amount of rainfall results in an increasing primary production (O'Connor *et al.*, 2001; Snyman and Fouché, 1993; Le Houérou *et al.*, 1988). The vegetation of a semi-arid rangeland shows a composition of different species that can be characterised by distinctive traits (Díaz *et al.*, 2002). However, for simplification, vegetation can be described by one dominant abstract perennial vegetation type which is characterised by two main components (cf. Müller *et al.*, 2007; Stephan *et al.*, 1998): (i) storage biomass, the vigour of the vegetation, and (ii) aboveground biomass, the grazeable parts of a plant, which include living and dead material. Both components are interlinked: storage supports the growth of aboveground biomass and aboveground biomass transfers energy, gained by photosynthesis, to the storage (Trlica, 2006; Wolfson and Tainton, 1999). This positive feedback between storage and aboveground biomass is characterised by a time lag that is triggered by the time of the year. The first process dominates at the beginning of a rainy season, while the second prevails at its end. In addition to precipitation livestock grazing is another elementary process that influences the vegetation dynamics (Walker, 2002; Skarpe, 1991). Thereby, livestock and aboveground biomass are connected via a negative feedback loop. A large number of livestock strongly reduces the amount of aboveground biomass. In turn, little aboveground biomass can support fewer animals sustainably. Another important component in semi-arid grazing systems is the management by a farmer. This management influences properties of the livestock herd, like the number of animals or their spatial location. Therefore, management indirectly affects the conditions of vegetation. In turn, depending on the management strategy the vegetation condition influences future decisions of a farmer.

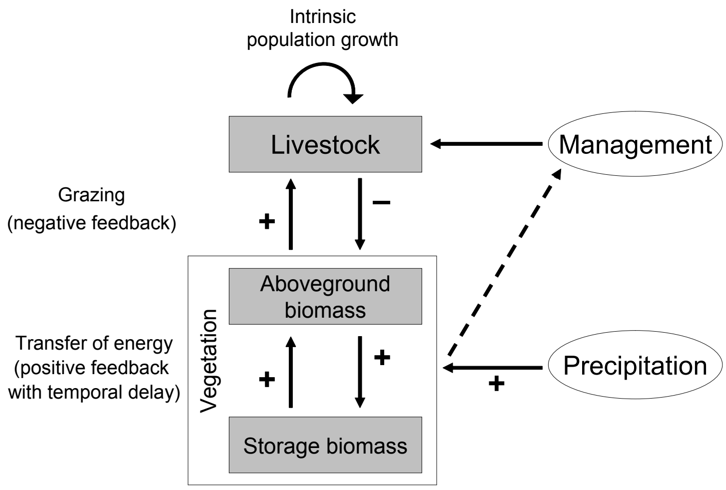


Figure 2.1: Conceptional description of semi-arid grazing systems. The figure shows relationships and feedbacks between main components. The dashed line indicates an optional relationship that is realised only for some management strategies.

In order to consider the characteristics of rotational grazing systems it is especially important to incorporate spatial and temporal components properly in the model. On the one hand, there is a need for intra-annual time steps, because different processes of rangeland dynamics changes during the course of the year. For example, the vegetation dynamics run through different phases within a year: major differences exist between rainy seasons, when growth processes take place, and dry seasons, when most plants in semi-arid regions are dormant. Furthermore, during the growth phase at the rainy season different processes are dominant at different times. Therefore, a grazing event affects the vegetation condition differently depending on the time, intensity, and duration of defoliation. Also, we consider intra-annual management decisions to allow an optimal adaptation to different situations. On the other hand, spatial processes have to be considered in the description of grazing systems. Grazing is normally not uniformly distributed within extensively utilised rangelands (Laca, 2009). Especially in rotational grazing systems, where the rangeland is subdivided by fences, livestock grazes only certain pastures at a time, while others are rested. Additionally, even within the fenced pastures the spatial distribution of grazing differs depending on several factors, like distance to water source and local vegetation conditions. This spatially and temporally varying distribution of grazing events in combination with intra-annually differing vegetation dynamics produces a heterogeneous pattern of rangeland conditions (Laca, 2000). In turn, this pattern might be considered in the planning of future spatial management decisions. Altogether, this accentuates the need for high temporal as well as spatial resolution of the rangeland model. This perspective was frequently neglected by other modelling studies which investigated grazing management either on an annual basis (e.g. Popp *et al.*, 2009; Müller *et al.*, 2007; Beukes *et al.*, 2002; Weber *et al.*, 2000; Stephan *et al.*, 1998), did not account for spatial interactions (e.g. Higgins *et al.*, 2007; Illius and O'Connor, 2000; Illius *et al.*, 1998; Noy-Meir, 1978), or simplified both aspects (e.g. Quaas *et al.*, 2007; Janssen *et al.*, 2004; Anderies *et al.*, 2002; Campbell *et al.*, 2000).

2.2 Model description

This section gives a description of the basic model framework that is used in the course of this thesis. Exact model specifications differ regarding specific research questions and are specified in each chapter with full detail. The structure of the model description follows the ODD (Overview, Design concepts, Details) protocol (Grimm *et al.*, 2010, 2006), which originally was developed for describing agent-based models but can be applied to other model types as well. The ecological knowledge incorporated in the model was gained from literature and interviews with rangeland scientists and farmers.

2.2.1 Purpose

The purpose of the model is to analyse commercial livestock management in semi-arid regions with the main focus on spatial and temporal management components. Particularly, the approach aspires a better understanding of how different management strategies – especially rotational grazing and stocking rules – affect ecological as well as economic variables of semi-arid rangelands over time. Primarily, the relevance of adaptivity in managing spatio-temporal heterogeneities in rangeland conditions should be investigated. Moreover, suitable strategies should be characterised and tested regarding their robustness under different climatic conditions.

2.2.2 Entities, state variables, and scales

The model simulates one farm in semi-arid rangelands that is utilized by livestock grazing. Spatial entities are single rangeland cells. The modelled area consists of 1024 cells on a rectangular grid (Fig. 2.2 B). Several cells are grouped to fenced paddocks that serve as grazing units. The state variables of the model comprise variables characterising (1) the abiotic environment: current amount of rainfall, season of the year (rainy and dry season), (2) different components of the vegetation on each rangeland cell (i.e. amount of storage, green and brown biomass), (3) spatial farm structure: amount and arrangement of fenced pastures and water holes, (4) livestock (number of individuals), and (5) management strategy of the farmer. Rangeland dynamics are modelled in discrete, weekly time steps, and

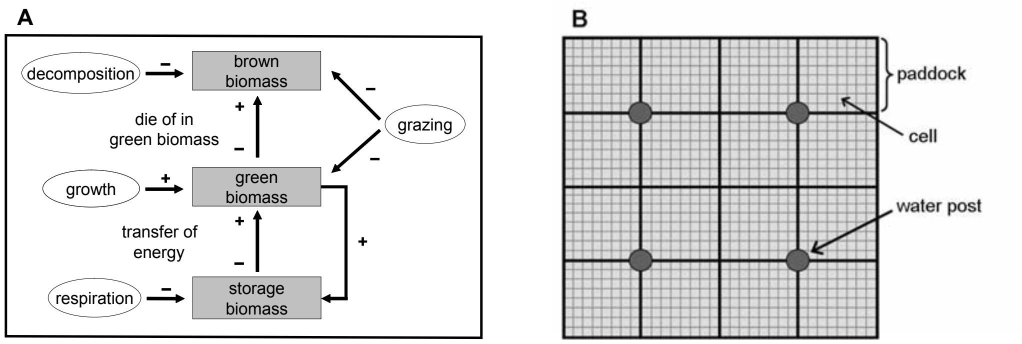


Figure 2.2: (A) Conceptional description of the vegetation dynamics. The figure illustrates the processes and relationships on a single rangeland cell. (B) Spatial layout of a farm (here divided into 16 paddocks consisting of 8x8 cells).

management decisions are taken on weekly or annual basis. The time span simulated is if not noted otherwise up to 100 years. A single cell represents several hectares, while the whole modelled rangeland would typically consists of up to thousands of hectare.

2.2.3 Process overview and scheduling

The model consists of six basic processes, which drive the rangeland dynamics: precipitation, vegetation dynamics, grazing, livestock population dynamics, livestock management (i.e. spatial rotation and herd size management), and management evaluation. Their scheduling is illustrated in Figure 2.3. The processes either take place every week (vegetation dynamics, grazing, and spatial rotation management), at a particular time each year (precipitation, livestock population dynamics, and stocking management), or once at the end of the simulation (management evaluation). At each time step, first the vegetation dynamics take place in each rangeland cell. Then, if applicable, the rotation management is conducted and afterwards, the grazing is scheduled. Once a year at the beginning of each rainy season the weekly amount of precipitation during the rainy season is set. At the end of the rainy season the weekly amount of precipitation is set to zero. Because most decisions regarding the herd size (i.e. stocking management of the farmer, and intrinsic population growth) are usually made towards the end of the rainy season (Holechek, 1988), in the model we assume one calving season per year that is timed directly after the rainy season. At the same time, the farmer makes the decision to regulate the stock size by trading livestock. At the end of the time horizon the outcome of the applied management strategy is evaluated. The following paragraphs shortly describe the model processes (for a detailed description see section 2.2.7).

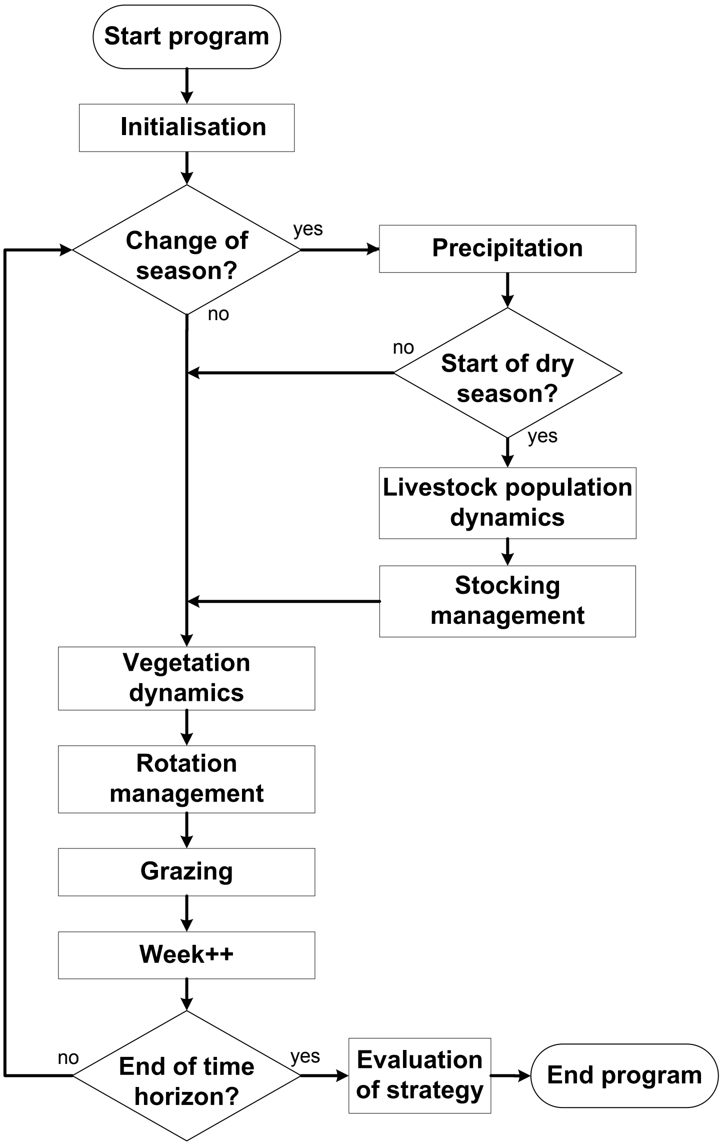


Figure 2.3: Flowchart of the rangeland model.

Precipitation Each year is divided into a rainy season that takes on average 18 weeks and a dry season that lasts on average 34 weeks. The weekly precipitation is randomly chosen from the underlying rainfall distribution and remains constant for one rainy season, while it is zero in the dry season. The beginning, the end, and therewith the length of the rainy season can vary stochastically within a certain range.

Vegetation dynamics This process simulates the weekly vegetation dynamics of one dominant perennial grass species on a single rangeland patch. The plant biomass is subdivided into three components (Fig. 2.2 A): (1) the storage biomass (also referred to as crown or reserve biomass) represents the vigour of the vegetation (Janssen *et al.*, 2004; Noy-Meir, 1982). (2) The green photosynthetically active and (3) the brown, dead biomass form the grazeable parts of the plants (aboveground biomass). The storage biomass contributes to the initial growth of green biomass by providing carbohydrates (after the first rainfall in the year or a strong grazing event) (Wolfson and Tainton, 1999; Stoddart, 1975). When the amount of green biomass increases, the green parts of the plants maintain their growth independently from the storage due to photosynthesis. Towards the end of the rainy season, carbohydrates formed by photosynthesis are transferred to the storage as reserves for regrowth in the next year (Trlica, 2006). After a severe depletion of green biomass by grazing the return of carbohydrates to the storage biomass is diminished resulting in a poorer regrowth in the following year (Stoddart, 1975). Brown biomass emerges from dying of green biomass at the end of the rainy season. Both brown and green biomass can be consumed by livestock.

Grazing The livestock has access to one single paddock at a time. In the respective paddock aboveground biomass can be grazed on all cells. Thereby, the intensity of livestock grazing on one cell depends on the total number of livestock on the paddock, the distance from the water post, quantity and ratio of green and brown biomass as well as a stochastic component of cell selection.

Livestock population dynamics The natural population dynamics of livestock on a farm are determined by intrinsic population growth. One calving season is scheduled at the end of each rainy season and the population growth is based on a linear relationship between growth rate and amount of forage intake during the previous year.

Livestock management The way a farmer determines the number and spatial distribution of livestock on the rangeland depends on the applied management strategy. This strategy is defined by three main characteristics: (i) farm structure, particularly the number of fenced pastures (paddocks), (ii) rotation rules for shifting livestock among the paddocks, and (iii) stocking rules for setting the number of livestock on the farm.

Management evaluation In order to compare different management options, ecological as well as economic variables that characterise the state of the rangeland system are observed at the end of each simulation.

2.2.4 Design concepts

Basic principles This model analyses principles of coupled human-environmental systems (Reynolds *et al.*, 2007; Liu *et al.*, 2007). In particularly, it investigates the tight link between the ecological and the economic component of semi-arid rangelands (e.g. Frank *et al.*, 2006; Janssen *et al.*, 2004; Perrings, 1997). The model is designed to analyse the management of spatio-temporal heterogeneities in semi-arid grazing systems (Laca, 2009; Vetter, 2005), like different spatial grazing and stocking rules. Also, it focuses on the importance of adaptivity in management approaches to achieve a sustainable utilisation of natural resources.

Adaptation and sensing Different components of the management strategy can be adapted to environmental conditions: the number of livestock is adapted to the current rangeland condition once a year, if an adaptive stocking rule (tracking of forage availability) is applied. Therefore, the farmer measures the available aboveground biomass at the end of each rainy season to determine the intended stock size that should not be exceeded. Moreover, the rotation rules adapt to different system properties. For example, the spatial distribution of livestock can be adapted to storage condition, amount of aboveground biomass or season of the year. Also, the standing time can be based on the amount of locally available forage.

Furthermore, livestock senses the biomass availability on a paddock to determine the local grazing distribution. Thus, intensity of grazing in each rangeland cell depends on the available amount and type of grazeable biomass as well as the distance to the water source.

Interaction The model implements an interaction between farmer and rangeland condition. A farmer determines the management decisions on the farm either via constant rules or by tracking the rangeland condition. In turn, amount and spatial distribution of livestock directly influences the condition on different rangeland cells. This produces a direct feedback, as the rangeland condition provides the basis of the farmers' livelihood and, depending on the management strategy, influences future decisions.

Emergence The condition of the three vegetation components as well as the actual number of livestock emerges from the rainfall pattern and the management strategy applied by a farmer. This strategy is either constant or adapts in return to vegetation condition and precipitation. Moreover the spatial pattern of vegetation condition on the farm depends on the number of paddocks, the distance from a water post, the duration and season of grazing, and the total number of livestock on the farm.

Stochasticity For stochastic rainfall scenarios the current precipitation for each rainy season is drawn from a log-normal distribution. The date of beginning and end of the rainy season is uniformly distributed within a certain range. Another stochastic model process is the spatial distribution of livestock grazing within one paddock. Besides other factors, including vegetation condition, number of livestock, and distance from the water source, the grazing intensity of each cell varies with a random factor.

Observation In order to analyse the model we observe the total number of livestock, the number of sold livestock per year, and the amount of storage biomass. Depending on specific questions different measures of these variables are recorded, like for example mean and variance of sold livestock over time, or spatial pattern of storage condition.

2.2.5 Initialisation

Each simulation starts at the beginning of the rainy season. If not specified differently, the state variables of the vegetation are initialised as follows: the amount of storage biomass is set to 80% of the maximal storage capacity, the amount of green biomass is zero, and the amount of brown biomass is set to 40% of its maximal capacity. The farm structure and the farmers' management rules are defined for the whole simulation.

2.2.6 Input data

The model does not include external input from field data, but precipitation is drawn annually from a probability distribution (see 2.2.7: Precipitation).

2.2.7 Submodels

All parameters of the model and ranges of their values are listed in Tab. 2.1.

Precipitation

In accordance with the seasonal rainfall pattern in semi-arid rangelands, which is characterised by a low and erratic annual rainfall, we distinguish two different phases per year: (i) the rainy season ($x_\mathrm{t} = 1$) with inter-annually fluctuating rainfall, and (ii) the dry season ($x_\mathrm{t} = 0$) without any rainfall. We assume the weekly amount of rainfall to be constant within one rainy season. Each year, it is drawn from a log-normal distribution (Sandford, 1982):

$$r = \mathrm{logNorm}(\ln(\overline{r}), \sigma_\mathrm{r}) \tag{2.1}$$

For a standard situation the mean rainfall $\overline{r}$ is defined to be 1, and the standard deviation σ_r is set to 0.25. These default values change under different climate

Table 2.1: Model parameters

parameter	range of value	description
$\overline{r}$	$[0, \infty)$	mean rainfall
σ_{r}	$(0, \infty)$	standard deviation of rainfall distribution
x_{t}	$\{0, 1\}$	season of the year (i.e. rainy (1) and dry (0) season)
$S_{\max}$	$(0, \infty)$	maximum capacity of storage biomass
K	$(0, S_{\max}]$	maximum capacity of aboveground (i.e. green + brown) biomass
m_{S}	$[0, 1]$	respiration rate of storage biomass
m_{B}	$[0, 1]$	decomposition rate of brown biomass
ρ_1	$[0, \rho_2)$	minimum required rainfall for growth
ρ_2	(ρ_1, ∞)	required rainfall for maximum growth $g_{\max}$
$g_{\max}$	$[0,\infty)$	maximum growth rate of green biomass
$a_{\max}$	$[0, 1]$	maximum storage transfer rate
τ_{S}	$[0, 1]$	upper threshold of storage support for green biomass growth
τ_{G}	$[0, 1]$	lower threshold of green biomass below which storage is not replenished
α	$[0, \infty)$	conversion rate from storage to green biomass
β	$[0, \infty)$	conversion rate from green to storage biomass
ψ	$[0, 1]$	preference of livestock for green biomass
$\mu_{\max}$	$[0, \infty)$	maximum annual growth rate of livestock
D	$(0, \infty)$	distance of a cell from a water post

scenarios. In the dry season, the weekly amount of rainfall r is always zero. The rainy season lasts on average four month (18 weeks). It consists of a fixed period of 14 weeks and a flexible beginning and end phase. In these flexible periods the exact weeks in which the rainy season starts and ends are drawn from a uniform distribution of four weeks each. The rainy season varies between 14 and 22 weeks, accordingly.

Vegetation dynamics

This process describes the biomass dynamics of a dominant perennial forage grass by a set of difference equations. In every rangeland cell, the biomass dynamics are simulated over several years in discrete weekly time steps. The biomass is divided into three different components: the storage biomass (S_{t}), the green photosynthetically active, palatable biomass (G_{t}), and the brown, dead biomass (B_{t}). The dynamics of the three components of biomass are interconnected by the following processes:

$$\Delta\, G_{\mathrm{t}} = \text{Growth of G} + \text{Support S to G} - \text{Dry up of G} \tag{2.2}$$

$$\Delta\, S_{\mathrm{t}} = \text{Translocation from G to S} - \text{Support S to G} - \text{Respiration} \tag{2.3}$$

$$\Delta\, B_{\mathrm{t}} = \text{Dry up of G} - \text{Decomposition} \tag{2.4}$$

The relation between storage and green biomass comprises of the energy transfer by carbohydrates during the rainy season. The initial growth of green biomass is supported by energy from the storage. With a growing amount of G leaf area and therewith photosynthesis increase and the growth becomes independent of the storage. With increasing G the storage biomass is replenished due to a transfer of energy from the photosynthetically active green biomass. At the end of the vegetation period the green biomass is drying up to brown biomass that is constantly decaying over time. Likewise, during the whole year the storage biomass is diminished by respiration. In the paragraph that follows we describe the model equations of the three vegetation components.

The storage biomass is diminished by a constant respiration rate (m_S), and due to the support of initial growth of green biomass at the beginning of the rainy season or after a severe grazing event. In turn, it is replenished from green biomass, which increases during the rainy season:

$$S_{t+1} = S_t + x_t \cdot \left[\underbrace{b(G_t) \cdot G_t \cdot \left(1 - \frac{S_t}{S_{max}}\right)}_{\text{Translocation from G}} - \underbrace{a(G_t) \cdot S_t}_{\text{Support of G}} \right] - \underbrace{m_S \cdot S_t}_{\text{Respiration}} \tag{2.5}$$

The season of the year is denoted by x_t that can either be one (rainy season) or zero (dry season). Apart from respiration all processes are limited to the rainy season. The function $a(G_t)$ calculates the fraction of S_t that is converted to support the growth of new green biomass (Eq. 2.6), S_{max} is the maximal amount of storage biomass, and $b(G_t)$ the fraction of G_t, that is used to build up storage biomass (Eq. 2.7). Hence, the linear functions $a(G_t)$ and $b(G_t)$ quantify the relation between storage and green biomass:

$$a(G_t) = \max\left(0\,,\, a_{max} - \frac{a_{max}}{\tau_S\, K} \cdot G_t\right) \tag{2.6}$$

$$b(G_t) = \begin{cases} 0, & \text{for } G_t \leq \tau_G\, K \\ \frac{\beta}{(1-\tau_G)\cdot K} \cdot (G_t - \tau_G\, K)\,, & \text{for } G_t > \tau_G\, K \end{cases} \tag{2.7}$$

K is the carrying capacity of aboveground biomass, which is determined by ground cover of the perennial grass. In the model, it is equal to the amount of storage biomass at the end of the previous rainy season. The support of the storage biomass for building up green biomass declines linearly with increasing G_t (Fig. 2.4 A). Here, a_{max} is the fraction of S_t that can at most be used each time step to build up green biomass. Parameter τ_S defines the threshold of G_t above which no more storage biomass is allocated to support the growth of green biomass. The fraction of green biomass G that is used to build up storage biomass increases linearly with the amount of green biomass (Fig. 2.4 B). Thereby, the conversion rate β defines the maximal amount of carbohydrates that one unit of green biomass can transfer to the storage. The threshold of green biomass below which no carbohydrates are stored in S_t is specified by τ_G. At the end of the rainy season most perennial plants transfer their energy to their storage organs

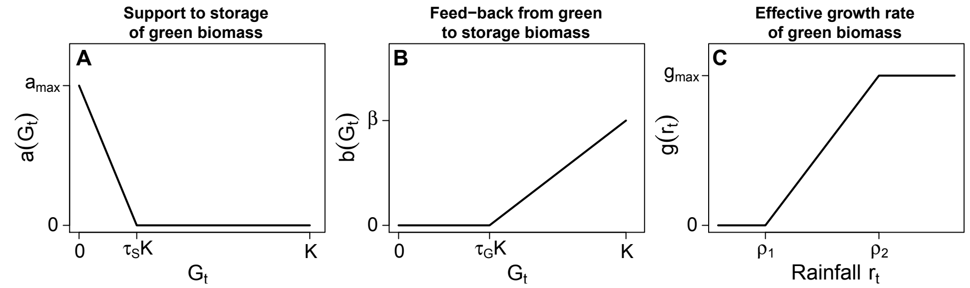


Figure 2.4: Visualisation of functions that describe certain model processes. (A) Support from storage to green biomass dependent on the amount of green biomass. (B) Feed-back from green to storage biomass dependent on the amount of green biomass. (C) Effective growth rate of green biomass dependent on precipitation.

(Trlica, 2006; Wolfson and Tainton, 1999). Therefore, in the model we assume a full feedback rate β during the last four weeks of the rainy season.

Changes in green biomass are characterised by continuous growth during the rainy season and a complete die off at the beginning of the dry season. Growth is initially supported by storage biomass, later maintained independently by photosynthesis until the end of the rainy season or until its capacity K is reached. The dynamics are described by:

$$G_{\mathrm{t}+1} = \min\Bigg(K,\, G_{\mathrm{t}} \,+\, x_{\mathrm{t}} \cdot \Bigg[\underbrace{g(r_{\mathrm{t}}) \cdot G_{\mathrm{t}} \cdot \left(1 - \frac{G_{\mathrm{t}}}{K}\right)}_{\text{Growth of G}} + \underbrace{\alpha \cdot\, a(G_{\mathrm{t}}) \cdot S_{\mathrm{t}}}_{\text{Support from S}} \Bigg] - \underbrace{(1 - x_{\mathrm{t}}) \cdot G_{\mathrm{t}}}_{\text{Dry up of G}} \Bigg) \tag{2.8}$$

Here, α is the conversion rate for storage turning into green biomass. The green biomass grows during the rainy season with an effective growth rate $g(r_{\mathrm{t}})$ that depends on the current precipitation r_{t} (Fig. 2.4 C):

$$g(r_{\mathrm{t}}) = \begin{cases} 0, & \text{for } r_{\mathrm{t}} \leq \rho_1 \\ \min\left(g_{\max}, \left(\frac{g_{\max}}{\rho_2 - \rho_1}\right) \cdot (r_{\mathrm{t}} - \rho_1)\right), & \text{for } r_{\mathrm{t}} > \rho_1 \end{cases} \tag{2.9}$$

Here, $g_{\max}$ stands for the maximal growth rate of green biomass. ρ_1 and ρ_2 are thresholds for the utilisation of available rainfall: ρ_1 defines the minimal required rainfall for growth and ρ_2 the highest usable rainfall that produces the maximal growth rate (Noy-Meir, 1981).

Brown biomass emerges from green biomass at the end of the rainy season:

$$B_{\mathrm{t+1}} = \min\Bigg((K - G_{\mathrm{t+1}}) \, , \, B_{\mathrm{t}} + \underbrace{(1 - x_{\mathrm{t}}) \cdot G_t}_{\text{Dry up of G}} - \underbrace{m_{\mathrm{B}} \cdot B_{\mathrm{t}}}_{\text{Decomposition}} \Bigg) \qquad (2.10)$$

It is affected by a constant decomposition rate m_B and limited by the capacity for the aboveground biomass K.

Grazing

Biomass consumption by large herbivores, i.e. domestic livestock like cattle or sheep has a major effect on rangeland condition. Furthermore, the impact of different kinds of livestock varies as they differ in dietary preference, nutrient requirements and foraging abilities (Stuth, 1991). However, in this model those species-specific differences are neglected, because the main focus lies on the effect of number and distribution of livestock in general. Hence, we presume a general definition of livestock in terms of Large Stock Units (LSU). In the model one LSU requires one unit of aboveground biomass per week.

Livestock grazing in semi-arid rangelands is heterogeneous in space and time. In the model the farmer chooses the paddock that is grazed at a certain time, but cannot influence the grazing pattern within the grazed paddock. Here, the impact of large herbivores, in particular the degree of herbage defoliation, is largely influenced by the distance from a water source (Andrew, 1988). Like different other modelling studies (Weber *et al.*, 1998; Jeltsch *et al.*, 1997; Pickup, 1994) we also emphasise the importance of this spatial component of grazing. Furthermore, green biomass has usually a higher palatability than brown biomass (Stuth, 1991; Walter and Volk, 1954). Also, a larger quantity of biomass will attract more defoliation. Therefore, in the model we calculate the relative grazing activity C per cell i as the product of a negative exponential decay function of the distance from the water source (Pringle and Landsberg, 2004), a term that accounts for the palatability and quantity of green and brown biomass, and a stochastic term:

$$C_{\mathrm{i}} = \exp(-D_{\mathrm{i}}) \cdot [\psi \cdot G_{\mathrm{i}} + (1 - \psi) \cdot B_{\mathrm{i}}] \cdot \mathrm{unif}(0,\, 1) \qquad (2.11)$$

where G_{i} is the green and B_{i} the brown biomass in a cell i, D_{i} the distance of the centre of cell i from the next watering point and ψ is the preference for grazing green biomass. Based on this, the relative frequency of livestock to graze in a certain cell i in relation to all other cells is given by $C_{\mathrm{i}}/\Sigma_{\mathrm{j}} C_{\mathrm{j}}$.

Hence, the absolute biomass discharge in each cell is given by the product of the relative grazing activity per cell and the total number of livestock on the farm. This discharge distributes among green and brown biomass according to the palatability and quantity of the two types. Thus, the weekly loss of green

($\widetilde{G}_\mathrm{i}$) and brown ($\widetilde{B}_\mathrm{i}$) biomass due to livestock grazing is calculated by:

$$\widetilde{G}_\mathrm{i} = \psi \cdot \frac{G_\mathrm{i}}{G_\mathrm{i} + B_\mathrm{i}} \cdot \left(\frac{C_\mathrm{i}}{\sum_\mathrm{j} C_\mathrm{j}} \cdot H_\mathrm{y} \right) \tag{2.12}$$

$$\widetilde{B}_\mathrm{i} = (1 - \psi) \cdot \frac{B_\mathrm{i}}{G_\mathrm{i} + B_\mathrm{i}} \cdot \left(\frac{C_\mathrm{i}}{\sum_\mathrm{j} C_\mathrm{j}} \cdot H_\mathrm{y} \right) \tag{2.13}$$

The discharge is weighted by the relative fraction of green, respectively brown biomass in a cell, as well as the preference of livestock for green or brown biomass (ψ or $(1 - \psi)$), and the number of livestock H_y that is present in the current year y. Subsequent to calculating the loss both biomass stocks are reduced respectively.

The calculated grazing activity for one cell can exceed the local availability of forage. In this case, the remaining forage demand is distributed to other cells also taking into account their distance, biomass conditions, and a random term. If the demand of forage exceeds the availability within the whole paddock, all available biomass is grazed. The deficit of forage is recorded and reduces the intrinsic population growth of livestock (see next paragraph).

Livestock population dynamics

The number of livestock on a farm is determined by both, intrinsic population growth and the management of the farmer (see also next paragraph). The model implements one calving season per year that is timed after the rainy season. It is based on a linear relationship between growth rate and amount of forage intake during the last year y:

$$H_\mathrm{y+1} = \mu_\mathrm{y} \cdot H_\mathrm{y} - S_\mathrm{y} \tag{2.14}$$

$$\mu_\mathrm{y} = \mu_\mathrm{max} \cdot \left(\frac{1}{52} \cdot \sum_{\mathrm{k}=0}^{51} \frac{F_\mathrm{k}}{H_\mathrm{y}} \right) \tag{2.15}$$

H_y is the number of livestock in the current year y, and S_y is the number of livestock sold (see paragraph 2.2.7 for determination of S_y). The annual population growth rate μ_y depends on the maximal population growth rate μ_max and the cumulated amount of forage that was grazed in the previous year. The grazed forage F_k quantifies the amount of aboveground biomass that is utilised by livestock in week k.

Livestock management

The way a farmer determines the amount and distribution of livestock on the rangeland depends on the applied management strategy. The strategy is defined by three main characteristics: (i) farm structure, (ii) rotation rules, and (iii) stocking rules. The following paragraphs describe the main elements of a management strategy. However, detailed information on specific arrangements are given in each chapter.

Spatial farm structure: The infrastructure on a farm is a major factor that determines possibilities and limits of the grazing management. The farm structure comprises farm size, number and size of paddocks, and arrangement of water posts (Fig. 2.2 B). The farm size is identical in all studies carried out in this thesis, but the number of paddocks in which it is subdivided differs. All paddocks in one setting have the same size and shape. Therefore, the paddock size is inversely proportional to the total number of paddocks. Each paddock has access to one water post. As several paddocks use the same water source it is located in one corner of each paddock.

Rotation rules: Most livestock farmers in semi-arid regions apply one of various kinds of rotational grazing schemes (Kothmann, 2009; Heady and Child, 1994). That means, the farmland is subdivided into several paddocks that are grazed in rotational sequence allowing recovery of rested paddocks. Thereby, the herd is shifted from one paddock to the next after a certain period of time. In the model, all livestock grazes on one camp at a time. Different rules for rotating the livestock herd among paddocks are implemented in the model. These rules include regulations that determine how long livestock remains on one paddock, and which paddock is grazed next. Both, the standing time on a paddock and the rotation sequence can either be predefined or adapt to different system characteristics, like available forage or storage condition.

Stocking rules: A very important aspect of rangeland management is the stocking strategy that determines the number of livestock on the farm (Holechek *et al.*, 1999b; Walker, 1995). The farmer manipulates this numbers by trading animals. In this study, decisions regarding the stock size are taken once a year after the rainy season. Two different types of stocking management (see e.g. Campbell *et al.*, 2006) are implemented in the model. On the one hand, the farmer can apply a constant stocking rule. This rule targets at a fixed number of livestock on the farm. The number is chosen at the beginning and stays constant during the whole simulation, regardless of any changes in rangeland conditions. On the other hand, the farmer can apply a more adaptive, so called opportunistic or tracking, stocking rule. This approach continuously adapts the livestock number to the available forage. At the beginning of a simulation, the farmer chooses a proportion of the available biomass that should be grazed each year. Henceforth, after each rainy season the number of livestock on the farm is adapted to this proportion of available aboveground biomass. For both rules the surplus of animals that exceeds the calculated herd size is sold.

Ecological-economic evaluation of management strategies

In order to analyse the different management strategies in terms of their appropriateness, we use criteria of ecological and economic sustainability. The state of the ecosystem is characterised by the amount of storage biomass. As economic parameters we use the amount of sold livestock as well as the herd size that can be supported on the farm. Different objectives are defined to allow an assessment of different management options and to analyse how they affect the range of suitable management options. In the course of this thesis, we use three main kinds of objectives:

(a) *Yield-maximising*: the farmer aims at maximum average yield over time and does not mind any fluctuations in this yield.

(b) *Mean-variance preference over yield*: the farmer balances a trade-off between high yield and low annual fluctuations in this yield regarding individual preferences.

(c) *Safety-first approach*: the farmer aspires to archive a certain minimum yield in most years.

A detailed description of the functioning of each objective is given in the respective chapters.

Chapter 3

Benefits of pattern-oriented parameterisation for generic models with an example from semi-arid rangeland management

3.1 Introduction

Natural resource management often intends to provide management strategies that are applicable to a broad range of situations while still covering the essential elements of the biological system. To this end, modelling is a well-established tool to investigate general management principles. There are basically two different approaches to natural resource modelling (Holling, 1966). On the one hand, specific and detailed (so called tactical/applied) models describe and predict how a particular system functions. Such detailed models pose the challenge of generalising results to a wider range of applications. On the other hand, generic (so called strategic/theoretical) models aim at a general understanding of a system. They describe the system in a more simple and parsimonious way to derive general insights about the functioning of main variables, drivers, processes and interactions. Despite their simplicity, these models are powerful tools to support the development of general management strategies and the formulation of policy (Conway, 1977). There are different ways how generic models can be analysed: either by investigating the whole parameter range (e.g. Woodward, 1998; Conway, 1977; May, 1976) or by considering mainly one default parameter set (e.g. van Noordwijk, 2002; Basset *et al.*, 1997). The first approach carries the risk of misleading system interpretation, if biologically implausible parameter constellations are included, e.g. for policy recommendations. Further obstacles arise with increasing model complexity, as analysis of the whole parameter range becomes more difficult and time consuming. The second approach, usually neglects a wide range of plausible model behaviour, which limits generality of the results. This dichotomy reveals the lack of established parameterisation methods for generic models that detect biologically realistic parameter sets. Such methods would bridge the gap between the two extreme approaches (of either analysing the whole parameter range or one default parameter set) and facilitate a more realistic but still general system analysis. In this study we propose such a new method for the parameterisation of generic models.

Generic models use simplified and aggregated descriptions to gain a general understanding of a system. Therefore, it is mostly impossible to measure certain parameters in the field directly. In this context, pattern-oriented modelling is one promising approach for parameter estimation (Grimm *et al.*, 2005; Wiegand *et al.*, 2004b, 2003; Grimm *et al.*, 1996; Grimm, 1994). It facilitates inverse parameterisation of models without direct field estimates of parameters by using multiple patterns on different hierarchical system levels, each pattern describing a certain characteristic aspect of the real system (Kramer-Schadt *et al.*, 2007; Wiegand *et al.*, 2004c). Pattern-oriented modelling is well-established for parameter estimation in specific case studies that use mostly quantitative patterns derived from field data (Rossmanith *et al.*, 2007; Pütz, 2006; Kramer-Schadt *et al.*, 2004; Wiegand *et al.*, 2004a). So far, however, it was never used to parameterise generic models for a general system analysis. In this case, mainly qualitative knowledge of the system behaviour is applicable to constrain parameter combinations to plausible ranges. This ensures generality of the results, whereas the use of single quantitative field measurements would limit the insights of the analysis to a specific situation. Here, we propose a pattern-oriented approach that uses qualitative patterns to describe general functional relations and thresholds of the investigated system. By using these patterns, we filter the whole parameter space to limit the range of parameter sets to those that describe plausible system dynamics. These parameter sets, which might still describe various different types of system behaviour, are then available for further model analysis.

An important field of application in natural resource management are semi-arid rangelands. Fundamental questions in these systems deal with the basic management strategies and policies that foster sustainable grazing management. For answering these questions, generic models have been repeatedly used to derive general management principles. In literature, we find both of the abovementioned types of model analysis: very simple analytical models that investigate a detailed analysis of the whole parameter space (Ibanez *et al.*, 2007; Perrings, 1994; Walker *et al.*, 1981; Noy-Meir, 1981, 1978, 1975), as well as models that focus on one single default parameter set (McAllister *et al.*, 2009; Müller *et al.*, 2007; Higgins *et al.*, 2007; Anderies *et al.*, 2002; Beukes *et al.*, 2002). In order to demonstrate benefits of our pattern-oriented parameterisation method, we use a generic vegetation model based on difference equations (chapter 2) to investigate semi-arid grazing management. Hence, we are interested only in those parameter sets that produce semi-arid vegetation dynamics. To separate all respective plausible parameter sets, the model is confronted with multiple patterns that describe the expected response of semi-arid vegetation under different rainfall and grazing conditions. Only if the model output matches all patterns simultaneously, a parameter set is accepted. Because the analysis aims at general conclusions, we use qualitative patterns instead of quantitative field data that would describe only one specific case. These patterns define boundaries of model response in relation to external impacts that are still accepted to describe semi-arid rangelands plausibly. For example, semi-arid rangeland systems are vulnerable to harsh environmental conditions (e.g. permanent droughts) and overutilisation. Hence, only parameter sets are accepted whose vegetation dynamics are characterised by vulnerable response to too low precipitation or too large livestock numbers. Finally, the parameterisation results in a pool of different parameter sets that all define possible forms of semi-arid rangeland dynamic. With this pool, a systematic analysis of the studied system can be accomplished, which helps to develop general and robust policy recommendations.

This chapter demonstrates a method for the parameterisation of generic models. This approach facilitates general insights in the targeted system without analysing the whole parameter space, but beyond the explanatory power of investigating single default parameter set. Therefore, we take a pattern-oriented approach using qualitative patterns to filter plausible system dynamics. This chapter consists of two parts. The first part presents the parameterisation approach: first, we describe the generic model, and specify the qualitative patterns used for parameterisation. Next, we explore the range of plausible parameter sets resulting from the parameterisation, and educe different functional response. We also discuss the resulting dynamics of functional types on different hierarchical levels. The second part of the chapter demonstrates the benefits of the proposed approach for the fervently discussed issue of optimal stocking management in semi-arid rangeland. We tackle the question of whether constant or opportunistic stocking strategies (Campbell *et al.*, 2006; Sandford and Scoones, 2006) are beneficial and how this depends on different model parameters. Finally, we combine both parts in a general discussion.

3.2 Pattern-oriented parameterisation of a generic rangeland model

3.2.1 Methods

This thesis investigates general principles of sustainable grazing strategies in semi-arid rangelands that are threatened by degradation mainly due to wrong management and climate change. Therefore, the purpose of our model is the simulation of vegetation dynamics in grazed ecosystems. Accordingly, the aim of the parameterisation is to detect only those parameter sets that plausibly describe dynamics of semi-arid rangelands. Only those parameter sets should be accepted whose dynamics are vulnerable within a desired range of external conditions. Consequently, dynamics that either stay stable or degrade always regardless of the external conditions must be excluded.

The model is based on the description of intra-annual processes like energy flows between different biomass components, and dynamics within these stocks (see chapter 2). For the parameterisation, however, we use qualitative patterns on different temporal scales (from one year to decades). These patterns describe outer boundaries and thresholds of a characteristic response of semi-arid rangelands to different external variables. Hence, the patterns function as filters to select parameter sets that produce feasible vegetation dynamics.

The rangeland model

In this study, we use a modified version of the rangeland model (see chapter 2). This model version does not include any spatial processes and simulates one single pasture in a semi-arid rangeland that is permanently utilised by livestock grazing. The modelled pasture would typically represent up to several hundred hectare. The reason for using the non-spatial model version is that we aim at parametersing the vegetation dynamics of rangeland cells that are driven by external factors (i.e. precipitation and grazing) only and do not directly interact between cells. The duration of the rainy season does not differ between years and is set to 18 weeks for all simulations. Because only values of parameters describing the vegetation dynamics are sought, intrinsic livestock population dynamics are not modelled explicitly. The stock size only changes due to livestock management by the farmer. In this non-spatial version of the model the biomass loss due to grazing depends only on the number of livestock on the pasture. It is allocated to green and brown biomass regarding their palatability and quantity, respectively. This means, the relative grazing activity given by the quotient $C_\mathrm{i}/\Sigma_\mathrm{j} C_\mathrm{j}$ in Eq. 2.12 – 2.13 is set to 1.

Livestock management As we use a non-spatial version of the model, stocking rules are the only management options that are available. For the parameterisation, we keep the stock size constant during each simulation. For the application study in section 3.3, two different stocking strategies are implemented. The first option is to apply a conservative stocking strategy and keep always a constant amount of livestock H_c on the farm. This amount is chosen at the beginning and stays constant during the whole simulation. The second option is an adaptive stocking strategy that continuously adapts the livestock number to the available forage. At the beginning of a simulation, the farmer chooses a proportion of the available biomass that should be grazed each year. Henceforth, after each rainy season, the number of livestock on the farm is adapted to this percentage ν of available aboveground biomass M_y. In the model one LSU requires one unit of aboveground biomass per week. Each year, the farmer stocks directly the calculated number of livestock. Accordingly, the annual stock size H_y is given by:

$$H_\mathrm{y} = \begin{cases} H_\mathrm{c} & \text{constant stocking} \\ \frac{\nu \cdot M_\mathrm{y}}{100} & \text{adaptive stocking} \end{cases} \tag{3.1}$$

The parameterisation approach

Semi-arid rangelands are vulnerable ecosystems that are threatened by degradation. They are exposed to external factors that affect the vegetation dynamics. In this regard, precipitation and grazing are known as major determinants (Wessels *et al.*, 2007; Fuhlendorf *et al.*, 2001; Fynn and O'Connor, 2000; Skarpe, 1992; Huntley and Walker, 1982). Therefore, we use qualitative patterns that describe the general response of the system to different rainfall and livestock number. In order to quantify the system behaviour, we observe changes in the following state variables: storage biomass, annual production of green biomass, and consumed biomass by livestock. The initial storage biomass differs for the analysis of different patterns (Tab. 3.1).

We select four different patterns that describe semi-arid vegetation dynamics. These patterns define (1) under which conditions the rangeland system degrades on the long run, and (2) when it recovers. Further, the patterns define that the rangeland should (3) provide to some extend enough forage to support livestock during the whole year, and (4) show a characteristic response of green biomass production to certain amounts of rainfall.

The patterns describe qualitative relations between state variable response and external variables. For example, high rainfall years generally should result in good rangeland condition, while poor rainfall should lead to decreased condition. On the other hand, the larger the permanent stock size is the larger the negative effect on range condition should be. Therefore, an increasing number of livestock together with a lower rainfall should increase the risk of degradation, while a rested pasture should be able to recover in good rainfall years.

In the following, we specify the four qualitative patterns that are expected to filter plausible behaviour of state variables. The knowledge used is gained from literature and interviews with rangeland scientists and farmers.

Pattern 1 - Degradation: One of the major threats in semi-arid rangelands all over the world is degradation. Different factors lead to a loss of vegetation cover and in turn, cause a reduction in animal productivity. It is heavily discussed to what extend grazing of naturally fluctuating livestock populations impact the vegetation in semi-arid rangelands (see Vetter, 2005; Briske *et al.*, 2003; Behnke *et al.*, 1993). Domestic livestock numbers, however, can be artificially maintained at very high levels (Archer and Smeins, 1991). Especially, in combination with low precipitation this has a substantially negative impact on the vigour of plants and therefore, the vegetation conditions. For this pattern, we define degradation as a decline in the rangeland condition that persists permanently under certain environmental and management conditions (Abel and Blaikie, 1989), however, in our definition this decline is not necessarily irreversible (q.v. Helldén, 1991). As indicator for degradation in our model, we define a loss of storage biomass at the end of the rainy season beneath a certain threshold.

In this pattern we determine limits of rainfall and grazing pressure, where the storage condition has to degrade definitely (Tab. 3.1). Furthermore, we assign a medium rainfall together with a conservative low stock size, where no degradation should appear. Simulations start with a storage biomass of 80% of its maximal capacity at the first year and run 25 years. Degradation is present, if the storage biomass falls under 10% of the maximum storage capacity. Thus, a parameter set is excluded, if the storage biomass falls bellow this threshold within 25 years. This pattern selects vegetation types that are to certain extend vulnerable to external variables. It excludes those types that respond too stable and those that hardy enable any livestock grazing.

Table 3.1: Values for external parameters that limit the range of plausible model parameters. The table shows the expected functional response of state variables.

Rainfall	Stock size	Initial storage biomass	Functional response
1.0	5	80%	No degradation & no forage shortage
0.5	2	80%	Degradation
0.35	0	80%	Degradation
1.0	34	80%	Degradation & forage shortage
0.5	34	80%	Degradation & forage shortage
2.9	8	25%	Recovery & no forage shortage
1.0	0	25%	Recovery
2.9	0	25%	Recovery
2.9	17	80%	No forage shortage
2.9	5	80%	No forage shortage
2.9	50	80%	Forage shortage
0.25 – 2.5	0	80%	Increasing biomass production

Pattern 2 - Recovery: The desired rangeland is expected to be resilient within certain boundaries. This means, rangeland must be capable to recover from a relatively poor condition under a favourable environmental situation (e.g. in sweet grassveld in southern Africa; Tainton, 1999). For this pattern we define a recovery of storage biomass from 25% of maximum capacity to at least 50% after 25 years as reasonable. Recovery should occur at high rainfall in combination with a conservative stock size as well as under medium precipitation on a rested pasture (Tab. 3.1). However, recovery that proceeds too fast is unrealistic. Therefore, we assume that the increase of range condition can not exceed 30% of total storage capacity per year.

Pattern 3 - Livestock feeding: Semi-arid rangelands can sustainably provide food resources for grazing ungulates. However, during droughts the size of livestock populations naturally crashes down, because of forage shortage (Owen-Smith, 1990; Ellis and Swift, 1988). Nevertheless, if numbers of domestic livestock are artificially maintained at too high levels (Archer and Smeins, 1991) the herd size can definitively reach an upper threshold where the requirements of the livestock permanently exceed the forage supply on the rangeland. Furthermore, Pickup (1996) found that herbage production and consumption by cattle decline substantially in dry periods. Therefore, we define that the type of rangeland we are interested in should be able to provide sufficient forage to feed at least a medium amount of livestock under average precipitation. Then again, in case of a very high livestock number especially under low rainfall a deficit in forage availability is expected. This assumption is supported by Fynn and O'Connor (2000), who also found rainfall to be a good indicator for cattle performance. In detail, this pattern describes points in the parameter space (Tab. 3.1), where the rangeland should definitely provide enough forage to satisfy livestock and others where livestock numbers are too high to feed all animals. To secure the sustainability of this forage supply a time span of 25 years is simulated.

Pattern 4 - Biomass production: Several studies found a strong evidence of a linear relationship of annual primary production and annual rainfall (O'Connor *et al.*, 2001; Paruelo *et al.*, 2000; Snyman and Fouché, 1993; Lauenroth and Sala, 1992; Le Houérou *et al.*, 1988). Hence, we assume an increase of the annual production of green biomass with increasing precipitation within predefined boundaries (Fig. 3.1). This relation is simulated for different levels of rainfall without any grazing. Thereby, either a too large production under low rainfall or a too low production under high rainfall are filtered out. Tab. 3.2 shows the simulated rainfall values together with the upper and the lower boundary of expected green biomass production. Produced green biomass is measured after one rainy season with duration of 18 weeks. Initial storage biomass is set to 80% of maximum capacity.

Table 3.2: Simulated rainfall values with upper and lower boundary of accepted values of produced green biomass (Pattern 4).

Rainfall	Lower boundary	Upper boundary
0.25	0.0	0.25
0.5	0.15	0.5
0.75	0.3	0.75
1.0	0.45	1
1.5	0.65	1
2.5	0.95	1

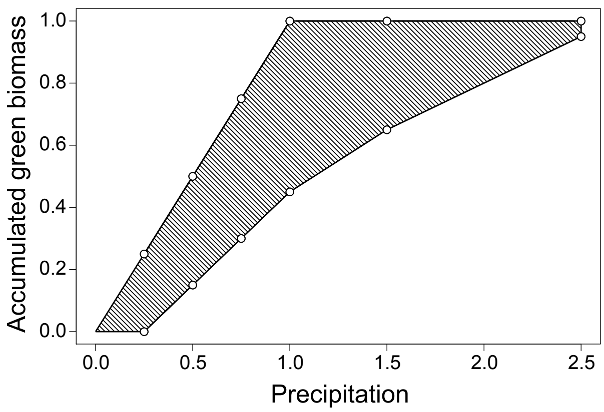


Figure 3.1: Expected green biomass production after one rainy season of 18 weeks (Pattern 4). The produced biomass of plausible parameter sets lies in the shaded area.

Table 3.3: Parameters of rangeland model. For parameterisation the parameters are varied in given ranges.

parameter	value range	description
m_{S}	$[0, 0.05]$	respiration rate of storage biomass
m_{B}	$[0, 0.05]$	decomposition rate of brown biomass
ρ_1	0	minimum required rainfall for growth
ρ_2	$[0.4, 3]$	required rainfall for maximal growth $g_{\max}$
$g_{\max}$	$[0, 3]$	maximum growth rate of green biomass
$a_{\max}$	$[0, 0.5]$	maximum storage transfer rate
τ_{S}	$[0, 1]$	upper threshold of storage support for green biomass growth
τ_{G}	0	lower threshold of green biomass below that storage is not replenished
α	$[0, 5]$	conversion rate from storage to green biomass
β	$[0, 1.5]$	conversion rate from green to storage biomass
ψ	0.9	preference of livestock for green biomass
$S_{\max}$	25000	maximum amount of storage biomass

Parameter sets and initialisation

In order to parameterise the rangeland model, we search for plausible combinations of eight model parameters. For simplification, we set the parameters ρ_1 and τ_{G} to zero, and ψ to 0.9 . We use Latin hypercube sampling (Saltelli *et al.*, 2000; Stein, 1987; McKay *et al.*, 1979) to create one billion random parameter sets. Tab. 3.3 shows all model parameters, including eight parameters that are varied within given parameter ranges. For hypercube sampling, each parameter range is equally divided into ten intervals. We run the model parameterisation for one pasture under continuous grazing. For each simulation run the defined values of precipitation and stock size remain constant. All values for external variables set in section 3.2.1 were defined with reference to a log-normal rainfall distribution with mean of 1 and variance of 0.25. The stock sizes refer to an area with maximum storage capacity of 25000 units and a forage requirement of 1 unit per LSU/week.

Each of the generated parameter sets is confronted with the four patterns. If simulation results do not match all requirements, the respective parameter set is excluded. Otherwise, it is accepted to produce plausible system dynamic and considered for further analysis.

The next section presents the results of the pattern-oriented parameterisation. We address three different hierarchical levels: (i) the impact on the level of parameter values, (ii) the resulting temporal model dynamics, and (iii) the aggregated model behaviour depending on different external factors.

First, the resulting range of each parameter as well as relations between parameters are investigated. Second, we show time series of the vegetation dynamic of some characteristic example parameter sets under mean constant rainfall and without grazing. Finally, in order to illustrate the behaviour of the system for single parameter sets under different external conditions, we visualise the potential risk of degradation as well as the potential for regeneration. Therefore, we use a two-dimensional input parameter space between different degrees of precipitation and grazing pressure. For each combination of rainfall and stock size a rangeland with initial storage biomass of 50% of maximum capacity is simulated over 25 years. Direction and speed in the change of storage condition are measured by the mean amount of storage biomass at the end of each rainy season.

3.2.2 Results

Influence of parameters

As result of the pattern-oriented parameterisation 11316 out of 10^9 parameter sets were accepted to produce plausible vegetation dynamic. Thereby, the range of several model parameters could be narrowed. Fig. 3.2 illustrates the realised parameter ranges and their distribution. Furthermore, Fig. 3.3 reveals interrelations between pair combinations of all parameters. In the paragraph that follows, we describe and explain some characteristic range limitations and interactions of all parameters.

For example, both parameters that cause a continuous decline in biomass stocks (i.e. m_{B} and m_{S}) mostly not exceed medium values of 0.03 (Fig. 3.2). This is due to the fact that on the one hand, parameter sets that cause a strong reduction in brown biomass lead to a shortage in forage especially at the end of the rainy season. This shortage occurs even under favourable conditions. On the other hand, increasing reduction in storage biomass requires an increasing regeneration ability of the system. This, however, can be vulnerable already under a low grazing pressure. In addition, a high decomposition rate of the storage m_{S} limits parameters that determine the investment of storage for initial growth of green

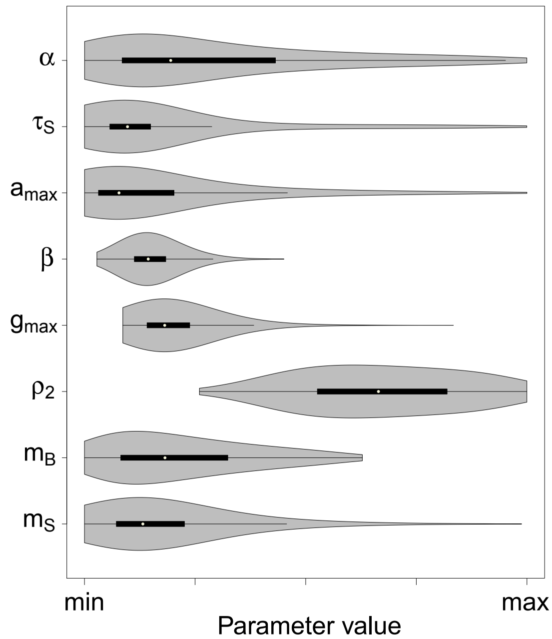


Figure 3.2: Realised parameter values. The violin plots show the accepted values of the parameters as a density distribution combined with a boxplot. Each plot ranges from minimum to maximum value of the parameter (see Tab. 3.3).

biomass (i.e. $a_{\max}$ and τ_{S}) to small values (Fig. 3.3). However, both parameters, $a_{\max}$ and τ_{S}, are not allowed be too small either. In this case the initial support for G would be too low to enable a full recovery of the depleted storage.

The parameter β, which determines the strength of the feedback from green to storage biomass, is constrained to values between 0.04 and 0.75. Too high values of β are filtered out, because a high conversion rate of green to storage biomass would lead to a system that is too robust against high stock size and low precipitation. On the other hand, if β would be too low, the regeneration ability of the storage is insufficient. Also, a strong positive interrelation between β and m_{S} is observed: an increasing respiration of storage biomass (m_{S}) requires a more efficient return of energy to the storage (β). In turn, if the conversion rate β is too low, a high respiration m_{S} would always lead to degradation of the storage biomass.

Concerning the production of green biomass, a small maximum growth rate $g_{\max}$ is not in accordance with the pattern imposed, because the forage production would be insufficient especially at a range of high rainfall values. In case of large $g_{\max}$ values the performance of green biomass depends strongly on the required rainfall for maximal growth ρ_2 (Fig. 3.3). Both parameters are interlinked. A certain minimum ratio $\rho_2 \,/\, g_{\max}$ is required to produce plausible dynamics of green biomass. Above this ratio several combinations are possible; combinations

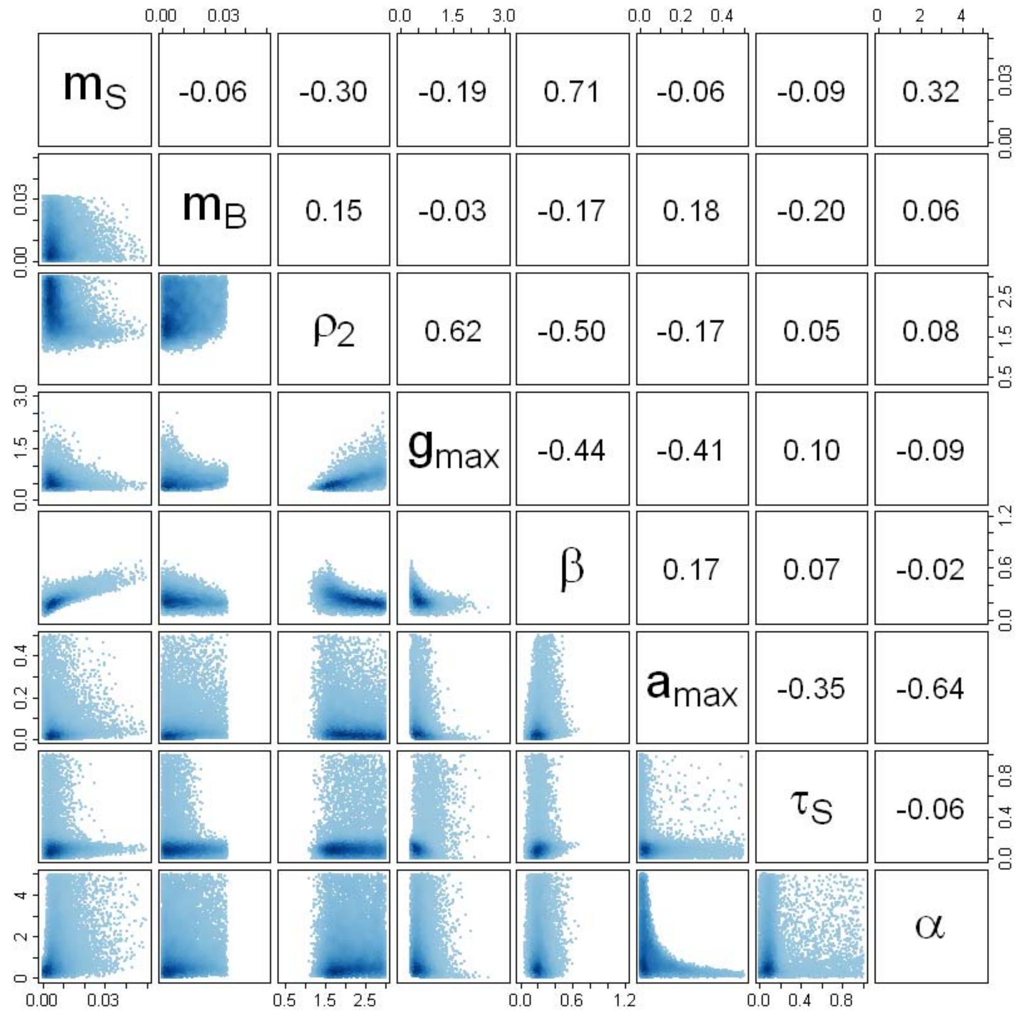


Figure 3.3: Correlation between model parameters for all accepted parameter sets. Pair-wise correlations are plotted for the whole tested range of the varied parameters (Tab. 3.3) in the lower left part of the figure. An increasing density of points is indicated by darker colours. The upper right part of the figure shows Spearman's rank correlation coefficients.

with a lower ratio would produce already at low rainfall values a huge amount of green biomass. For the same reason ρ_2 values below a medium rainfall of 1 are not suitable. Depending on $g_{\max}$ they would also result in either an immoderate production under low or an insufficient production under high rainfall.

Moreover, large parameter values for $a_{\max}$ and τ_S are rarely accepted (Fig. 3.2), because they lead to a strong decline in storage biomass during the rainy season. This requires particular values for the other parameters to ensure a sufficient feedback of reserves at the end of the rainy season. The two parameters show a loose negative correlation. There are only very few parameter sets with a combination of medium to high values for both parameters. As mentioned above, such parameter combinations are unfavourable, because they result in a severe and long depletion of storage biomass at the beginning of the rainy season that demands efficient recovery.

The parameters $a_{\max}$ and α show a strong negative correlation. A combination of high values in both parameters is impossible, because this would result in extremely high initial green biomass and in turn causes too large biomass production under low rainfall conditions. Due to the same reasoning, low values of α are generally more common.

Biomass dynamics

Due to the basic structure of the model, all different plausible parameter sets show similar characteristic temporal dynamics in the three components of vegetation (see Fig. 3.4 for one characteristic example): storage biomass declines at the beginning of the rainy season and increases at its end. During the dry season it declines continuously. In contrast, green biomass usually starts with a short strong increase at the beginning of the rainy season. Afterwards, it shows logistic biomass growth until the end of the season, when it drops to zero. Overall aboveground biomass (i.e. green and brown biomass) constantly declines in the dry season followed by an increase during the rainy season under favourable conditions. This increase is parallel to the amount of green biomass unless the aboveground biomass reaches its carrying capacity. However, even if all parameter sets show the same basic behaviour, they differ in detail. We can distinguish different functional types of vegetation dynamics, albeit the transition between them is smooth. Some characteristic features of vegetation response are visualised in Fig. 3.5. The corresponding parameter sets are shown in Tab. 3.4.

Table 3.4: Parameter values of selected example parameter sets.

Type	m_S	m_B	ρ_2	$g_{\max}$	β	$a_{\max}$	τ_S	α
A	0.004	0.0095	2.3	0.52	0.191	0.111	0.02	0.96
B	0.0033	0.0113	1.3744	0.3459	0.2094	0.3898	0.0706	0.2512
C	0.0097	0.0053	1.186	0.3374	0.3895	0.2015	0.116	0.2025
D	0.0025	0.0087	1.9575	0.6228	0.2651	0.0264	0.432	0.2285
E	0.0006	0.0125	2.5569	0.4761	0.1672	0.0181	0.2374	0.6506
F	0.0072	0.0055	1.8134	0.5812	0.287	0.004	0.47	2.2107

Storage biomass is characterised by different magnitudes of biomass loss and regain during one year. This attribute is determined by the constant respiration rate and the intensity of investment in initial green biomass growth. The types differ particularly in magnitude and duration of investment as well as intensity of respiration. More precisely, the stronger the respiration (m_S) or the larger the investment (τ_S and $a_{\max}$), respectively, the stronger the required feedback (β) at

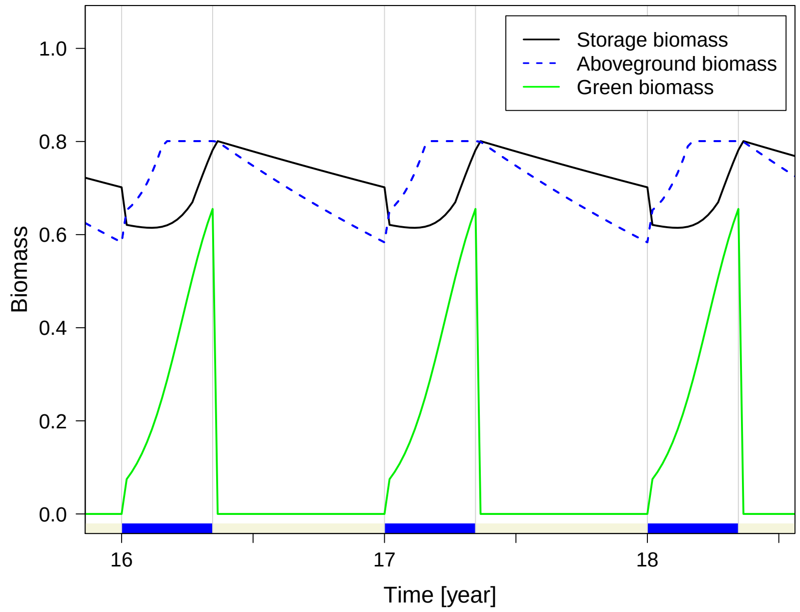


Figure 3.4: Example of intra-annual vegetation dynamic for one single parameter set. The relative values of storage, green and aboveground (green + brown) biomass are plotted over three years with medium rainfall and no grazing. Vertical bars indicate change between rainy (blue) and dry (beige) season.

the end of the rainy season to provide sufficient recovery (Fig. 3.5). Furthermore, the amount of storage biomass at the end of the rainy season differs among parameter sets under the same conditions. Some types maintain a larger storage biomass under medium precipitation than others.

The dynamics of green biomass at different functional types differs mainly in the way it benefits from the initial support from storage biomass (α). This dynamic varies between two end points: there is either a strong increase at the beginning of the rainy season (Fig. 3.5 A – B) or a slow start of biomass growth (Fig. 3.5 D – F). The types also differ in their strength of independent growth ($g_{\max}$ and ρ_2), which results in different total amounts of produced biomass per year.

Again, the total aboveground biomass shows different levels of biomass loss during the dry season. This is mainly determined by the decomposition rate m_{B}.

These different functional characteristics of vegetation are combined in various different ways. Fig. 3.5 A – B for example, reveal a short investment from storage to green biomass that mirrors in a strong initial growth of green biomass. After one week, this support ends and regenerations slowly starts. Both dynamics are mostly similar, but differ in the strength of investment and the amount of storage regain. However, even if the investment in green biomass of type B exceeds the investment of type A largely, it leads roughly to the same initial growth.

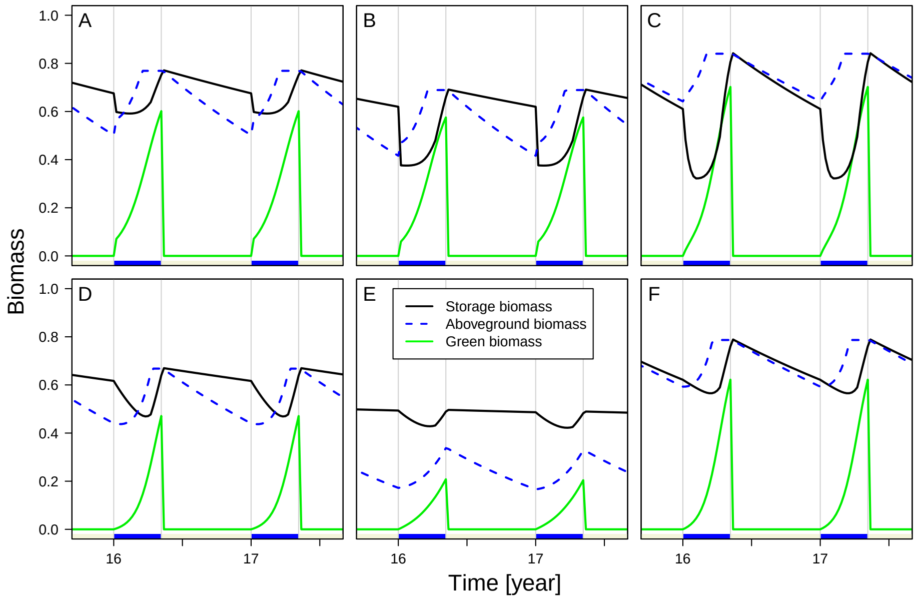


Figure 3.5: Intra-annual vegetation dynamics for six characteristic parameter sets (Tab. 3.4). The relative values of storage, green and aboveground (green + brown) biomass are plotted over two rainy seasons with medium rainfall ($r = 1$) and conservative grazing ($H = 5$). Vertical bars indicate change between rainy (blue) and dry (beige) season.

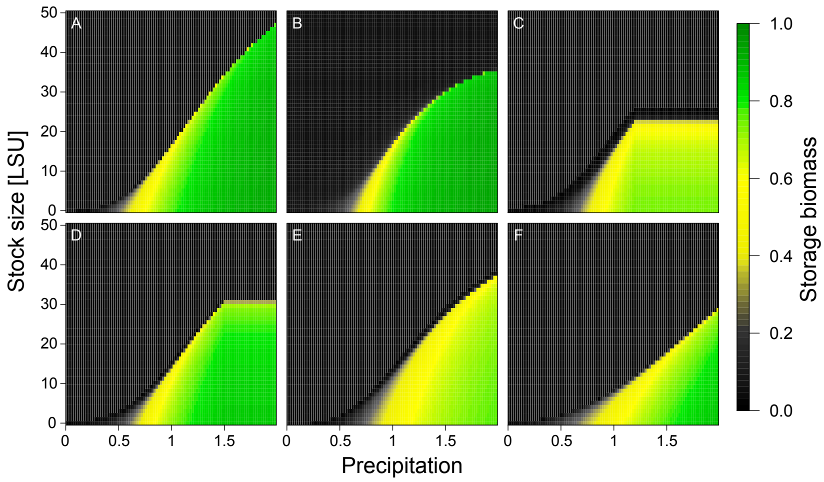


Figure 3.6: Functional response (i.e. degeneration or regeneration) of six functional vegetation types (see Tab. 3.4) in relation to precipitation and grazing pressure. Figures show the storage biomass after 25 years. The initial value for the storage biomass was set to 50% of the maximum capacity.

In contrast, both types shown in Fig. 3.5 D – E, are characterised by longer but lesser investment in green biomass. Type D invests more and reaches a higher amount of green and in turn aboveground biomass. On the other hand, the biomass production of type E remains poor and, therefore, the overall aboveground biomass stays below capacity. Moreover, its total amount of storage biomass is relatively low.

Fig. 3.5 C illustrates one plant type with high annual transformation in storage biomass that is caused by high respiration rate and strong support of green biomass. The storage investment is high and takes place for an mean period of time. A similar respiration of the storage characterises type F. However, this type provides hardly any support to initial green biomass growth, but utilizes this low input efficiently.

Vulnerability profile

The potential risk of degradation as well as the potential for regeneration is visualized for different combinations of precipitation and grazing pressure. Fig. 3.6 illustrate the parameter space for the above shown example parameter sets (Tab. 3.4). Generally, as a direct consequence of the patterns used for parameterisation, for all parameter sets low precipitation and high grazing pressure leads to fast degradation, while high precipitation and low grazing pressure results in a quick regeneration of storage condition. Between these extremes, there is a gradual transition. In particular, the shape of this transition zone differs for different types. For example, type A is very robust against either low precipitation or high grazing pressure, while type F appears vulnerable already at medium precipitation or moderate stock size. All types have a certain maximum stock size, above that the rangeland degrades always. However, this threshold in stock size as well as the precipitation when it is reached differs for different types. Types C and D reach this point at rather low rainfall values. This indicates that these types hardly benefit from above average rainfall events. Also the width of the transition zone, where the magnitude of degradation or regeneration is low, differs between types. Compared to type E and F the transition zone of type A and D is narrower, particularly the part towards full regeneration (yellow to green). On the other hand, type B and C are characterised by a wider area of light degradation, while all other types show a very sharp transition.

3.3 Sample application: Constant vs. adaptive stocking management

The pattern-oriented parameterisation extracted parameter sets that deliver plausible vegetation dynamic. This facilitates further studies, because we do not have to consider all possible regions within the whole parameter space, but can still cover all plausible vegetation responses. In order to illustrate the benefits of the parameterisation method, we examine the optimal stock size. Several studies discuss the benefits of constant versus adaptive (also called opportunistic) stocking (e.g. Campbell *et al.*, 2006; Sandford and Scoones, 2006). In this context, we hypothesize that specific characteristics of vegetation have great influence on the suitability of a management strategy. With our approach, we can estimate which livestock management is more beneficial for which functional type of vegetation. This is an important question, as adaptive stocking generally increases the costs of rangeland management. Hence, it is an important issue under which circumstances it is advisable to adapt the stock size continuously to the available forage. To examine this questions, we first apply the successful sets of the parameterisation to the example of optimal stocking management. Second, we compare the gained results to an approach of random parameter sampling and demonstrate the benefits of the parameterisation approach.

3.3.1 Methods

Comparison of stocking strategies

In order to estimate the influence of the functional vegetation type on the favourable management, we determine the maximum possible mean stock size for both, a constant and an adaptive stocking approach for all accepted parameter sets. For this purpose either a constant stock size is defined for the whole simulation time or the stock size is annually adapted to the available aboveground biomass after the rainy season (see section 3.2.1). As output variable the maximum value of mean livestock numbers that can be supported by the rangeland is calculated. This maximum stock size is defined as the largest number that can be feed in more than 95% of all years at one simulation. Therefore, we simulated 100 runs over 25 years and calculate the mean of all years and simulations. The simulations are conducted under stochastic fluctuating annual precipitation drawn form a log-normal distribution with a mean value of 1 and a variance of 0.25. In the end, results are compared by the relative difference in stock size D_S between both strategies:

$$D_\mathrm{S} = \frac{\overline{H}_\mathrm{adapt} - \overline{H}_\mathrm{const}}{\overline{H}_\mathrm{adapt}} \tag{3.2}$$

$\overline{H}_\mathrm{const}$ is the maximal possible mean constant stock size, while $\overline{H}_\mathrm{adapt}$ represents the mean stock size that is maximal possible under an adaptive strategy.

Comparison of parameterisation approaches

In order to demonstrate the difference between the pattern-oriented parameterisation approach compared to an investigation of the whole parameter space we

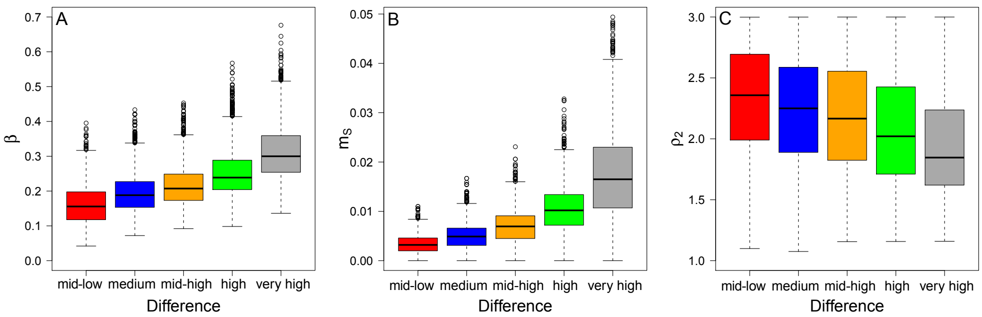


Figure 3.7: Difference in maximum stock size between adaptive and constant stocking in relation to certain parameters. The difference is grouped in five classes. The figures illustrates the three parameters with the most evident impact, namely (A) conversion rate of green to storage biomass β, (B) respiration rate of storage biomass m_S, and (C) required rainfall for maximal growth ρ_2.

conduct the same analysis with random sampled parameter sets. We generate also 11316 parameter sets with Latin hypercube sampling within the ranges used for pattern-oriented parameterisation (Tab. 3.3) and compare them with all plausible parameter sets derived from the pattern-oriented approach. Again, for all samples the difference in the highest possible stocking number derived by constant and adaptive stocking is calculated (p.v. section 3.3.1).

3.3.2 Results

Constant vs. adaptive stocking

In this paragraph, we compared the maximal possible mean stock size of adaptive and constant stocking for all plausible parameter sets (see section 3.2.2). We find that the adaptive strategy is always better than the constant strategy. For the intended range of vegetation types, the maximal possible yield lies at least 25% higher. However, the magnitude of this benefit varies. In order to detect the important processes that drive this difference, we group the parameter sets depending on the difference D_S into five equal sized classes for detailed analysis.

Mainly two parameters have significant influence on the management results (Fig. 3.7 A – B). An increase in parameter β, which determines the efficiency in replenishing storage during the rainy season, tends to result in a larger difference between both strategies (Fig. 3.7 A). By trend, this large difference is also caused by a high decomposition rate m_S (Fig. 3.7 B). Both parameters determine the magnitude of storage loss and regain during one year and are interlinked by a strong positive correlation (Fig. 3.3). This relationship mirrors in the average temporal dynamic of the storage biomass (Fig. 3.8). The larger the difference between adaptive and constant stocking strategy, the more distinct the average extent of storage loss and regain.

The influence of ρ_2 is not as distinct (Fig. 3.7 C), but in general lower ρ_2-values result more often in larger differences between the strategies. The vegetation types characterised by a low ρ_2 cannot take advantage of good rainfall years to compensate a too strong grazing pressure in years with low rainfall. By trend, this exhibits a sustained decline in storage biomass.

Furthermore, the combination of the parameters a_{max} and τ_{S} is an important indicator for a huge difference between both management strategies (Fig. 3.9). If both parameters have a medium to high value, which indicates a strong and long support of storage to green biomass, D_{S} is definitively very high. These parameter combinations are always attended by low values of storage respiration (m_{S}). However, also low values in one or both of these parameters can lead to a very high difference D_{S}.

All critical parameters that strongly influence the performance of a strategy are related to dynamics in the storage biomass. Altogether, adaptive stocking is definitively advisable for functional types with high storage respiration and high efficiency in carbohydrate storage. Moreover, this applies to types with strong investment of storage biomass and to some extent low ρ_2-values. Overall, these characteristics indicate functional types that are more vulnerable to high livestock numbers than others. Thereby, the strong storage loss must be replenished each year to secure a viable rangeland condition. Elsewise, degradation occurs quickly. Conclusively, storage dynamics are the most important processes to analyse stocking strategies and adaptive stocking is particularly beneficial for vegetation types that are vulnerable to storage degradation by overgrazing.

Comparison between random and pattern-oriented parameterisation

The previous paragraph showed results gained by an analysis using the pattern-oriented parameterisation approach. As, the advantage compared to an investigation of the whole parameter space is not directly evident, this paragraph compares both approaches.

The comparison indicates clearly the benefit of our parameterisation approach (Fig. 3.10). The pattern-oriented method reduces the parameter space and therewith, the possible system behaviour. Fig. 3.10 A shows that the resultant sample set of parameter combinations leads to significantly different outcome than random sampling. Random sampling results in a very large number of cases, where the stocking strategy makes nearly no difference, while another peak lies in the range of maximal difference. Both extremes are never or rarely archived by plausible parameter sets found by the pattern oriented parameterisation that describe the intended rangeland type. This indicates that random sampling overlays the actually important outcome by the huge amount of results emerged from implausible parameter sets.

Furthermore, there is no distinct impact of single parameters on the difference between adaptive and constant stocking for the random sampling (Fig. 3.10 B).

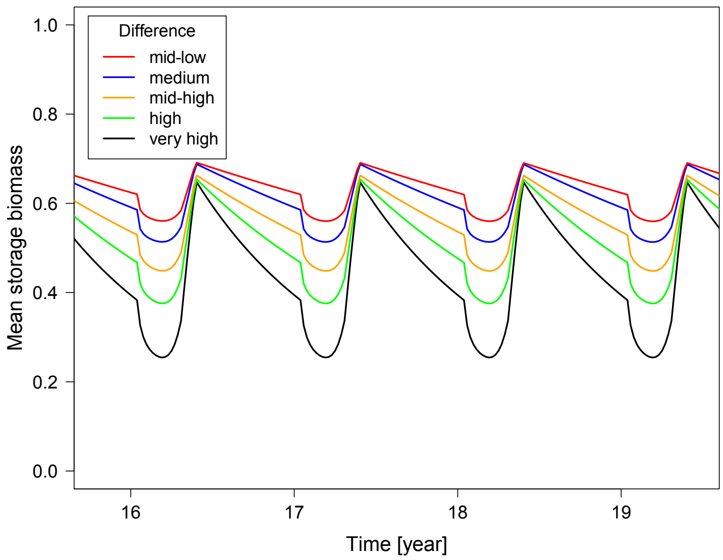


Figure 3.8: Average temporal dynamic of storage biomass for the five classes of relative difference between constant and adaptive stocking. Each line represents the average of all parameter sets that belong to the particular class. Storage dynamics are simulated under medium rainfall and without grazing.

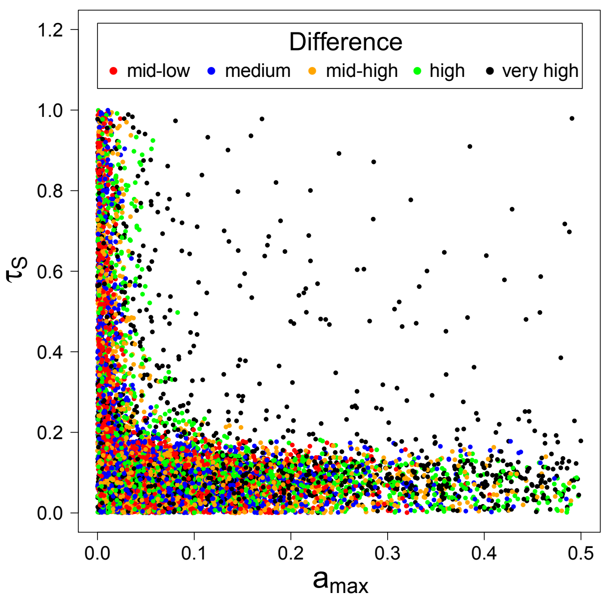


Figure 3.9: Location of parameter sets in the $a_{\max}$-τ_S parameter space, relating their difference between constant and adaptive stocking.

Each difference can be achieved by nearly all parameter values. In contrast, the pattern-oriented approach reveals correlations between value of single parameters (e.g. m_S and β) and the difference between the stocking strategies (see also section 3.3.2). All this highlights the suitability of preselecting parameter sets due to qualitative patterns (see section 3.3) to facilitate a more focused analysis and a straightforward interpretation of the results.

3.4 Discussion

Generic models aspire to create general insights into a system instead of analysing a specific situation. Therefore, it is necessary to cover the whole range of possible system behaviour in the analysis to formulate general management principles. However, it is mostly not useful to consider regions in the parameter space that lead to implausible results. Therefore, we propose a pattern-oriented parameterisation approach that separates parameter combinations which describes plausible system dynamics to facilitate further model analysis.

This chapter points out that it can be vitally important to focus on the parameter range of a generic model that reproduces the characteristic behaviour of the system to answer specific questions. In our study, the applied model has a broader range of possible outcome than is typical for semi-arid rangelands. The differentiation between typical and non-typical dynamic behaviour and between appropriate and inappropriate parameter sets was found to be decisive for the question of the merits of adaptive stocking over constant stocking. There is a clear difference in the results our model produces for the whole parameter space compared to results that are generated by plausible parameter sets (Fig. 3.10). In this case, analysing the whole parameter space would lead to different predictions of the system behaviour and possibly to incorrect policy recommendations. This underpins the importance of a method that identifies relevant model behaviour and therefore, avoids drawing wrong conclusions.

In this regard, pattern-oriented modelling with qualitative filters is a useful approach to characterise typical system behaviour. Because the model incorporates the most essential processes and mechanisms that determine the interaction between different components of vegetation in a general way, the model shows a very broad range of system responses. Building on that, the use of qualitative patterns was beneficial to constrain parameter sets to those combinations that reproduce typical characteristics of semi-arid vegetation dynamics. The advantage of qualitative patterns is their generality that does not limit the model results to one specific situation or case study. Nevertheless, the combination of such qualitative patterns is still powerful enough to exclude untypical behaviour (Grimm *et al.*, 2005). However, such patterns are only available for systems where extensive research already provides general understanding, like for semi-arid rangelands or tropical rain forests. It is not applicable for situations where new fields of research

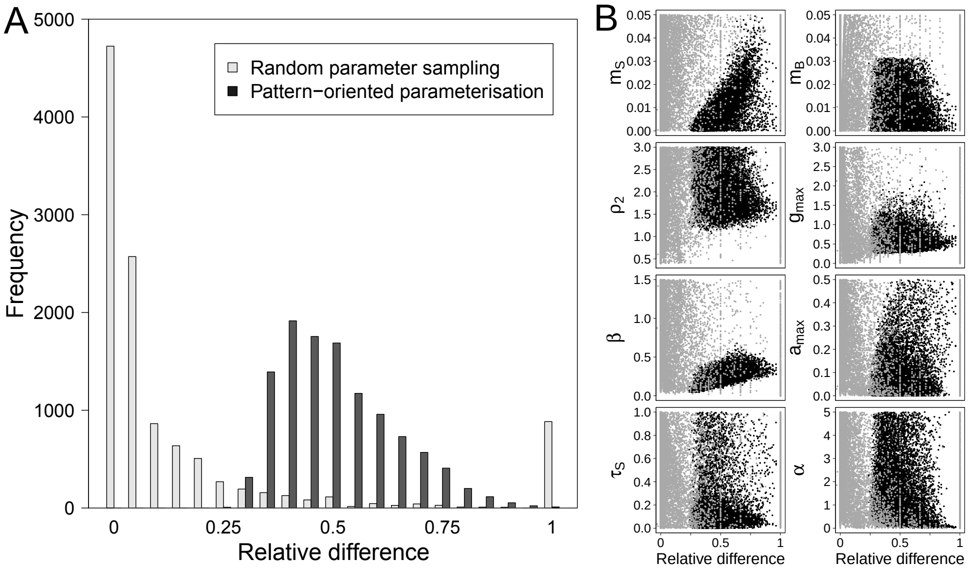


Figure 3.10: Comparison between random parameter sampling over the whole parameter space and pattern-oriented parameterisation approach. For each approach 11316 parameter sets are considered. (A) Distribution of relative difference between constant and adaptive stocking for both approaches. (B) Relation between the difference and each parameter separately (note that black dots are plotted first and overlayed by grey dots).

are entered and, hence, only little system understanding exists so far. Here, the analysis of the whole parameter range will provide general insights to possible model behaviour or quantitative patterns can help to build up knowledge for a specific case study.

Beside the selection of parameter sets for further analysis, the result of the parameterisation itself already establishes an understanding of the model, and therefore, interactions and dynamics of the intended system (i.e. semi-arid vegetation). This understanding is gained on different hierarchical system levels: on the basic level of the model equations, the resulting parameter sets provide insights on functioning and interplay of different model processes. They reveal what interrelations and trade-offs characterise semi-arid rangelands and their characteristic vulnerability to degradation. Further, we investigate what kind of system dynamics emerges from patterns and model structure. The complex interplay of all parameters is examined at the level of temporal system dynamics. The behaviour of different state variables (i.e. storage, green and brown biomass) indicates the existence of different functional types of dynamic response. Furthermore, a higher level of aggregation (e.g. vulnerability profile) shows the impact of different external factors (i.e. rainfall and grazing pressure) on the long-term system response. Actually, this viewpoint visualises the model response directly on the level of the patterns. In case of Fig. 3.6 degradation and recovery pattern are exemplified, which set outer limits to storage biomass development. Such systematic analysis increases the insights to the modelled system and helps the interpretation of future results.

Even if most parameters of generic models are impossible to measure directly in field studies, they often describe well-known processes and mechanisms of a real system. This enables a comparison of functional types described by plausible parameter sets to real plant types (Díaz *et al.*, 2002) of semi-arid rangelands. This link would help to integrate the gained results in a practical context and facilitates more applied management recommendations. However, already at this stage, the presented method facilitates the analysis of management questions and identifies important parameters that give hints, which vegetation type should be managed in which way. For our example of optimal stocking management, it was beneficial to cover only plausible system dynamics instead of screening the whole parameter space. The analysis of the whole space suggested that the full range of possible outcomes is realised (Fig. 3.10 A). However, most sets result in extremes, either no or a rather strong difference between both strategies. Contrary to implication of these results, it became obvious, that all types of rangeland system we are interested in benefit at least to some extent from an adaptive stocking strategy. On the other hand, the filtered rangeland types represent rarely a situation where only adaptive stocking is able to maintain livestock grazing (i.e. $D_{\mathrm{S}} = 1$). Moreover, our approach fosters mechanistic understanding of relevant processes that determine the kind of response to management strategies. Mostly factors that control the dynamics of storage biomass appear to be important. In this regard, storage respiration rate (m_{S}), capacity to recover storage biomass (β) as well as intensity of storage investment (i.e. interdependency between $a_{\max}$ and τ_{S}) have a high significance. Such knowledge could be used to formulate rules of thumb to support management decisions. In our case it would be strongly advisable to apply an adaptive stocking strategy for vegetation types that are characterised by a large intra-annual deviation in storage biomass (i.e. strong loss of storage biomass during the beginning of a year followed by a strong regain at the end).

Altogether, we agree with Campbell *et al.* (2006) that "one size does not fit all", because different environmental conditions favour different stocking regimes. Hence, modelling approaches that are tailored to one specific study region or rather use only one default parameter set could possibly also derive different more general results, if they would investigate a broader range of plausible parameters. Therefore, these analyses might not suffice to draw general conclusions (and need to be expanded to other biologically plausible parameter areas).

This study did not focus on economic and social components that are also important elements of management strategies (Campbell *et al.*, 2006). For example, our results are based on the number of livestock a rangeland can support and do not account for any price variability. However, the magnitude of these price fluctuations influences the economic benefit gained by a certain strategy (Sandford and Scoones, 2006; Campbell *et al.*, 2000). Thereby, our results might change, as adaptive strategies are known to be economically more feasible under minor price fluctuations (Sandford and Scoones, 2006).

Overall, the complexity of our model and, therewith, the variety of functional behaviour was already too large to classify similar parameter sets straightforward in manageable amount of groups. Either the resulting groups would have been too heterogeneous to extract a distinct behaviour or the amount of groups would have been unmanageable large. Nevertheless, we could still differentiate functional behaviour of particular state variables (i.e. vegetation components).

This study, considered only one default scenario of precipitation. However, different geographical regions are characterised by different climates and climate change might alter present situations (Knapp *et al.*, 2008). Hence, in one further step the influence of climatic conditions (i.e. mean and variance of precipitation) on the suitability of the stocking strategy should be analysed. There might be conditions that give advantage to adaptive and others to constant stocking strategies. Furthermore, this chapter investigated only continuous grazing on one pasture. Space, however, is an important factor of grazing management (Laca, 2009; Vetter, 2005) that is often neglected in rangeland modelling. Therefore, the spatial component of grazing will be the central subject of the next chapters.

Altogether, the presented method showed both scientific and applied relevance. On the one hand, it offers an alternative for the analysis of generic models, in addition to the investigation of the whole parameter space or a single parameter set. This parameterisation process facilitates already a basic mechanistic understanding of the investigated system. On the other hand, it provides a tool to support a more realistic analysis of management approaches to derive general rules of thumb and assist management recommendation.

Chapter 4

Linking farmers' objectives and environmental constraints in rotational grazing systems

4.1 Introduction

Interactions in coupled human-ecological systems are manifold and complex (Reynolds *et al.*, 2007; Liu *et al.*, 2007). Especially in semi-arid rangelands, where extensive livestock farming is the predominant form of land-use, ecological and economic components are tightly linked (Frank *et al.*, 2006; Perrings, 1997). In these regions, uncertain and highly variable climatic conditions cause low and erratic primary production that in turn poses a major challenge to grazing management. In order to ensure the long-term ecological as well as economic sustainability flexible and viable management strategies are essential. Particularly, on commercial rangelands, where farm borders prevent the formerly widespread large scale moving of traditional pastoral systems (Coughenour, 1991; Walker *et al.*, 1981), arises the need for new, well adapted grazing strategies for risk management on a local scale. In this regard, rotational grazing strategies are expected to be suitable for sustaining rangeland conditions while increasing economic yield (Savory and Butterfield, 1998; Savory and Parsons, 1980). However, there might not be a universal management approach for every situation, because a viable strategy must coevally suite individual needs, goals and abilities of livestock farmers and account for local environmental conditions (Sandford, 1982). Hence, a general understanding of the relations between ecological, climatological, and socio-economic factors is needed (Asner *et al.*, 2004) to assist individual management planning and decision making. Accordingly, this study uses ecological-economic modelling to tackle the questions: What are important characteristics of viable grazing strategies in semi-arid rangelands and how do they depend on individual objectives and environmental conditions?

Four main principles of grazing management are widely accepted (Walker, 1995): (i) timing as well as (ii) spatial distribution of grazing, (iii) kind of livestock, and (iv) stocking rate. Based on these principles various kinds of (rotational) grazing systems emerged that are used in practice (Kothmann, 2009;

Tainton, 1999; Savory and Butterfield, 1998; Heady and Child, 1994; Heitschmidt and Taylor, 1991; Holechek, 1983). However, the strength of the impact of the different factors is heavily discussed. Whereas many authors emphasise the high importance of an appropriate stocking rate (Batabyal *et al.*, 2001; Walker, 1995; Holechek, 1988), there are ongoing discussions on the importance of timing and spatial distribution of grazing and in particular even on the suitability of rotational grazing systems in general (Briske *et al.*, 2008; Barnes *et al.*, 2008).

Also, the design of a specific strategy as well as the overall outcome of the rangeland management must always serve the objectives of the individual land manager (Sandford, 1982). These objectives vary, however, depending on many social factors of which the economic is usually dominant (Connor, 1991). In this regard, farmers can for instance aim to maximise their income, or they might be risk averse and try to minimise the fluctuation in the income. Another option would be trying to ensure a minimum income in every year. In summary, the variety of different objectives is as manifold as the diversity in management strategies itself.

Although the management goals of a farmer are important variables in the choice of the appropriate strategy, moreover, it is limited by local factors such as environmental conditions or available resources. These conditions (e.g. rainfall regimes) vary widely in drylands between geographical locations and may require locally adapted management approaches. In addition, an effective risk management becomes even more important under expected consequences of climate change. A decrease in precipitation is predicted for some parts of the arid and semi-arid regions over the next century (IPCC, 2008). Generally, an increased frequency of extreme weather events is expected (Hoffman and Vogel, 2008; IPCC, 2007; Easterling *et al.*, 2000). Therefore, it is crucial to know how management strategies perform under which climatic conditions and which are robust over a wide climatic range.

In this chapter we systematically explore the relations between grazing strategies, management objectives and environmental conditions in semi-arid rangeland management. We tackle the question, which kind of strategy is applicable to satisfy certain objectives of livestock farmers. Therefore, we investigate rotational grazing strategies that are characterised by the degree of subdivision of the farmland (paddock number), standing time per paddock, and stocking rate of livestock. To evaluate the suitability of each strategy we use two different objectives: (i) an optimisation approach following mean-CV preferences, as well as (ii) a safety-first approach. Moreover, the relation of strategies and objectives are analysed under different climatic conditions and the robustness of results is tested. Finally, we exemplary show how different objectives can be combined to support decision making in rangeland management.

4.2 Methods

4.2.1 Model settings

This study uses the full spatial version of the rangeland model (chapter 2). The analysis focuses on both the management strategy of the farmer and the economic evaluation of the stochastic income distribution at the end of the time horizon. In order to elaborate a systematic analysis of the different levels (i.e. abiotic environment, grazing management, and economic evaluation) all simulations in this chapter are conducted for one characteristic vegetation type (i.e. one specific parameter set, see chapter 3.2.2, Type A). The parameter values of this vegetation type and other model parameters used this study are shown in Tab. 4.1.

Table 4.1: Parameter values of the model

parameter	value	description
$S_{\max}$	2500	maximum capacity of storage biomass
m_{S}	0.04	respiration rate of storage biomass
m_{B}	0.0095	decomposition rate of dead biomass
ρ_1	0.0	minimum required rainfall for growth
ρ_2	2.3	required rainfall for maximum growth $g_{\max}$
$g_{\max}$	0.52	maximum growth rate of green biomass
$a_{\max}$	0.111	maximum storage transfer rate
τ_{S}	0.02	upper threshold of storage support for green biomass growth
τ_{G}	0	lower threshold of green biomass below which storage is not replenished
ψ	0.9	preference of livestock for green biomass
α	0.96	conversion rate from storage to green biomass
β	0.191	conversion rate from green to storage biomass
$\mu_{\max}$	1.33	maximum annual growth rate of livestock

4.2.2 Management strategies

The farmer can affect the probability distribution of the income by choosing a certain grazing management strategy. The management strategies considered in this study are characterised by the rules for selling livestock, as well as the number of fenced pastures (paddocks), the standing time, and the stocking rate. Also, different precipitation scenarios are analysed.

Spatial farm structure

The modelled rangeland is subdivided into 1024 cells on a rectangular grid. These cells are grouped to paddocks that serve as grazing units. The number of paddocks is a variable of the farmer's management strategy. In the model, all paddocks have the same size and a quadratic shape. Therefore, the size of each paddock (i.e. how many cells it consists of) is endogenously determined by the number of paddocks. This study investigates continuous grazing on one large paddock and different degrees of subdivision into paddocks.

Rotation rules

In this chapter, we analyse a non-adaptive rotation management. This means, the herd is shifted from one paddock to the next after a fixed period in time (denoted by ST). Furthermore, the selection of the next paddock follows a fixed sequence without considering the biomass condition on the paddocks. Thereby, always the paddock that rested longest is grazed next.

Stocking and selling rules

At the beginning of the dry season, the farmer makes the decision to sell livestock to cover expenses and to regulate the stocking density. In this study, the farmer applies adaptive (also called opportunistic or tracking) stocking rules. The stocking rules differ in their intended stocking rates. For all strategies the maximum number of livestock $H_{\mathrm{max,\,y}}$ is adapted to the currently available forage supply on all paddocks that will be grazed in the next year M_{y}, and the stocking rate ν that is the percentage of available forage M_{y} that should be used:

$$H_{\mathrm{max,\,y}} = \frac{\nu \cdot M_{\mathrm{y}}}{100} \tag{4.1}$$

Stocking rates of more than 100% can be reasonable, because new biomass will be produced during the year within the next rainy season.

Also, we assume that the farmer only raises own animals and never purchases livestock. To cover at least some fixed costs always 10% of the livestock are sold at the beginning of each dry season. Additionally, the farmer sells the surplus of animals that exceed the estimated maximum herd size $H_{\mathrm{max,\,y}}$. For calculating the surplus the updated livestock number after reproduction is considered (for calculation of reproduction rate μ_{y} see chapter 2.2.7). Therefore, the number of sold livestock S_{y} is calculated by:

$$S_{\mathrm{y}} = 0.1 \cdot \mu_{\mathrm{y}} \cdot H_{\mathrm{y}} + \max(0, 0.9 \cdot \mu_{\mathrm{y}} \cdot H_{\mathrm{y}} - H_{\mathrm{max,\,y}}) \tag{4.2}$$

The farmer derives all income from selling livestock. Assuming that livestock prices are constant over time, livestock sales and income are the same, and both terms are used interchangeably in the following.

4.2.3 Economic evaluation of the management strategies under different objectives

In order to evaluate different management strategies from the economic perspective in terms of their appropriateness and to provide insight into the role of the farmer's management objectives, two different management aims are compared. In the first case (Obj_1), we consider a risk-averse, utility maximizing farmer (Quaas *et al.*, 2007) whose utility positively depends on the mean number $\overline{S}$ of livestock sold and negatively on the coefficient of variation $CV(S_\mathrm{t})$. In the second case (Obj_2), we assume that the farmer follows a safety-first approach (Baumgärtner and Quaas, 2009; Müller, 2006; Telser, 1955; Roy, 1952) and intends to avoid the economic risk that the yearly number of sold livestock S_t falls too often below the minimum threshold S_min required for securing the livelihood. "Too often" means more frequently than a critical number of years Y_max that can be tolerated at maximum within 10 years. Note that this number Y_max can also be interpreted as indicator of risk aversion: low/large Y_max-values indicate high/low risk aversion.

4.2.4 Simulation settings

In order to analyse which kind of management strategy suites the abovementioned management objectives best, we test a broad range of management strategies and their performance under several climate scenarios. The analysed rotational grazing strategies differ in number of paddocks, standing time, and stocking rate. We define rotation rules by combining several paddock numbers (4, 8, 16, 32) with fixed standing times (1, 2, 4, 8, 17, 52 weeks). Additionally, we simulate continuous grazing on one paddock. To set the stocking rule, we apply a broad range of stocking rates (20%, 50%, 80%, 110%, 140%). All management strategies are simulated for different climate scenarios. The scenarios differ in inter-annual variance of rainfall σ_r and mean precipitation $\overline{r}$ (Tab. 4.2).

Table 4.2: Table of climate scenarios.

Scenario	Mean rain $\overline{r}$	Variance of rain σ_r	Description
R_1-$\mathrm{V}_{0.25}$	1	0.25	average mean rainfall with average variance
R_1-$\mathrm{V}_{0.4}$	1	0.4	average mean rainfall with increased variance
$\mathrm{R}_{0.8}$-$\mathrm{V}_{0.25}$	0.8	0.25	decreased mean rainfall with average variance
$\mathrm{R}_{0.8}$-$\mathrm{V}_{0.4}$	0.8	0.4	decreased mean rainfall with increased variance

We simulate all management strategies for a period of 100 years. For each climate scenario the simulations are repeated 1000 times with differing stochastic precipitation. For the analysis of Obj_1 we calculate the mean number of livestock sold ($\overline{S}$) and their coefficient of variation (CV) for each run and averaged the two quantities over of all 1000 runs. In order to evaluate Obj_2 we calculate how often within ten years the yearly number of sold livestock S_t falls below the minimum threshold S_min.

4.3 Results

4.3.1 Herd and selling dynamics

All management strategies applied in our study lead to an inter-annually fluctuating livestock number and thus to an inter-annually unstable income from livestock sales. These fluctuations are caused by the variability of weather conditions as well as previous grazing history on the pastures.
If we compare different rotational grazing strategies applied under exactly the same precipitation regime, we observe different dynamics in herd size and income (Fig. 4.1). Tab. 4.3 shows the appendant mean and coefficient of variation (CV) of herd size and sold livestock over the simulated time span.

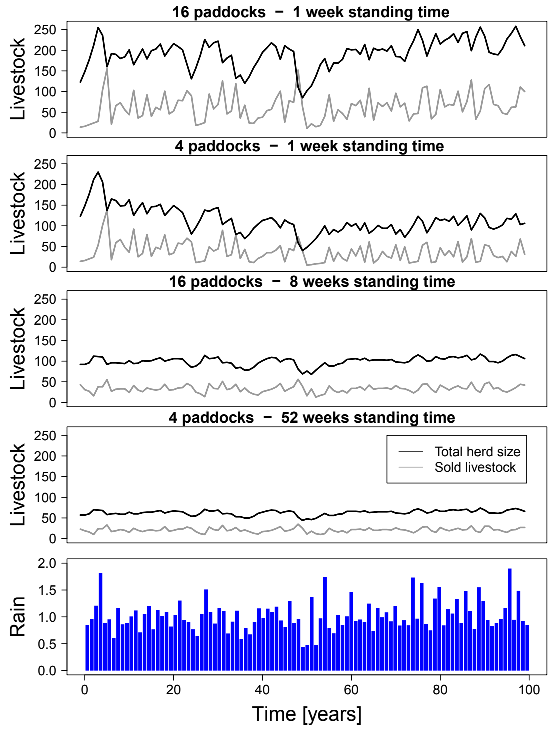


Figure 4.1: Herd size and income out of livestock sales over one simulation run of 100 years. Different management strategies are compared under the same rainfall regime and a stocking rate of 50%. The undermost graph shows the weekly amount of precipitation in each year.

For example, the standing time of one week on a farm divided into 16 paddocks results in a greater mean income ($\overline{S}_{16\text{p-1w}} = 62.85$) and a lower coefficient of variation ($CV_{16\text{p-1w}} = 0.514$) than on an otherwise similar farm with only four paddocks ($\overline{S}_{4\text{p-1w}} =$ 36.61 and $CV_{4\text{p-1w}} = 0.657$). On the other hand, a strategy working with weekly rotation on four paddocks compared with eight weeks stand-

Table 4.3: Mean values and coefficient of variation (CV) of herd size and sold livestock for examples shown in Fig. 4.1

Management strategy	Mean herd size	CV herd size	Mean sales	CV sales
16 paddocks - 1 week	192.87	0.182	62.85	0.514
4 paddocks - 1 week	113.11	0.282	36.61	0.657
16 paddocks - 8 weeks	99.84	0.101	33.19	0.259
4 paddocks - 52 weeks	62.86	0.097	20.88	0.251

ing time on 16 paddocks leads nearly to the same mean income ($\overline{S}_{\text{4p-1w}} = 36.61$ vs. $\overline{S}_{\text{16p-8w}} = 33.19$), but the CV is much higher on the farm with fewer paddocks and faster rotation ($CV_{\text{4p-1w}} = 0.657$ vs. $CV_{\text{16p-8w}} = 0.259$). This is caused by a more evenly utilisation of the pastures in case of the longer standing time on eight paddocks. Here, the higher local grazing pressure forces livestock to graze parts of a paddock with larger distance to the water point and in turn enables a longer resting of other paddocks. A similarly low degree of income variability like for the 16 - paddocks - 4 - weeks - strategy is obtained by changing to an extremely high standing time with few paddocks (52 weeks on 4 paddocks, $CV_{\text{4p-52w}} = 0.251$). However, this goes along with an extreme decrease in the mean income of more than 30% ($\overline{S}_{\text{16p-8w}} = 36.61$ vs. $\overline{S}_{\text{4p-52w}} = 20.88$), because only a fourth of the whole farm is grazed per year.

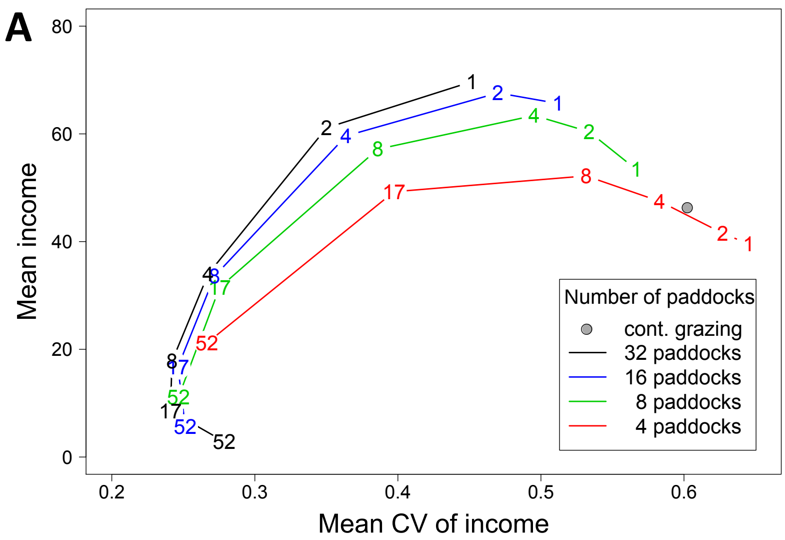
Generally, under all applied management strategies, years with low rainfall result in a temporary larger income, on the cost of an adaptation of herd size due to lower forage production. On the other hand, a high precipitation leads initially to a lower income, because more animals are kept to increase the size of the herd.

4.3.2 Management aiming at maximum stable income

As the first objective, we assume that the farmer is risk-averse with preferences of the mean-CV type, i.e. the farmer prefers a high mean income ($\overline{S}$) at a low coefficient of variation (CV). An economically efficient strategy is one that maximizes mean $\overline{S}$ at a given coefficient of variation CV, or, alternatively, a strategy that minimizes the CV at a given $\overline{S}$ of livestock sales.

Influence of paddock number and standing time

The combination of paddock number (PN) and standing time (ST) shows a strong impact on both $\overline{S}$ and CV (Fig. 4.2 A). An increasing standing time leads to a typical shape of the resulting curve in the mean-CV-space: the CV first decreases and then increases again for very long grazing periods on small paddocks. The mean income $\overline{S}$ shows a unimodal response; it first increases and then decreases with standing time. This indicates the existence of an optimum ST for increasing the mean income. We also see that the entire curve and this optimum ST shift



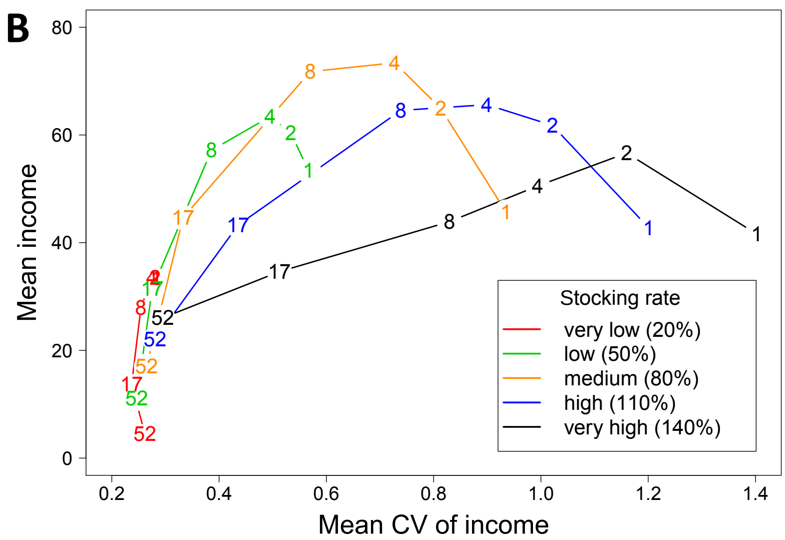


Figure 4.2: Relation between mean ($\overline{S}$) and coefficient of variation (CV) of the income from livestock sales for different management strategies. The numbers on the curves indicate the standing time per paddock in weeks. (A) The relation is plotted for different paddock numbers indicated by different colours at a stocking rate of 50%. The gray dot shows the outcome for a continuous grazing strategy. (B) The influence of different stocking rates is shown for a farm divided into eight paddocks.

with the PN. A simultaneous increase in paddock number and with a decrease standing time cause both an increase in the mean income $\overline{S}$ and a decrease in CV. Therefore, a higher subdivision of the farm combined with an appropriate (and higher) rotation speed improves the efficiency of a farm enterprise in terms of higher income and lower CV. However, in return the farmer's effort in management will probably increase with more paddocks and faster rotation. An optimal strategy therefore requires finding the appropriate balance between CV and $\overline{S}$ minus the effort cost.

Another finding is that a continuous grazing strategy performs very poorly (Fig. 4.2 A). It provides a rather low mean income at an extremely high degree of uncertainty. This means that a continuous grazing strategy is dominated by most rotational grazing strategies.

Influence of stocking rate

Increasing the stocking rate (SR) from a very low level leads initially to a higher mean income at the cost of an increasing CV (Fig. 4.2 B). But at some point a further increase of the stocking rate results in a diminished mean income combined with even higher fluctuations. This means that increasing the stocking rate beyond this critical value would be inefficient. A similar pattern is observed for different paddock numbers (results not shown). Here, the critical point of the stocking rate where both, income and CV, perform worse is rising with increasing PN. We conclude that a higher number of paddocks enable to some point a higher stocking rate.

4.3.3 Management for sustaining a minimum income

We now change the perspective and repeat the analysis for a different specification of the farmer's objectives (Obj_2). This means that we consider a farmer who intends to obtain a certain minimum income from livestock sales $S_{\min}$ but tolerates a maximum number of years $Y_{\max}$ where this minimum is not attained.

For this analysis, we assess all management strategies regarding their suitability to meet the management objective (Fig. 4.3). This is repeated for different values of $S_{\min}$ and $Y_{\max}$ to assess the influence of the farmer's minimum requirements and capacity to tolerate failing the minimum. First, we focus on a stocking rate of 50%. Fig. 4.3 A reveals that both the income requirements and the tolerance of failure of the farmer markedly limit the range of suitable strategies. If the minimum income requirement is low or the tolerance is high, almost every strategy is found to be suitable. With increasing minimum income requirements or decreasing tolerance, however, the range of opportunities is shrinking. Long ST or small PN become increasingly critical. The suitable strategies are characterised by an appropriate ratio of paddock number and standing time (i.e. the higher the PN the shorter the ST). Altogether, there is only one type of strategies that is

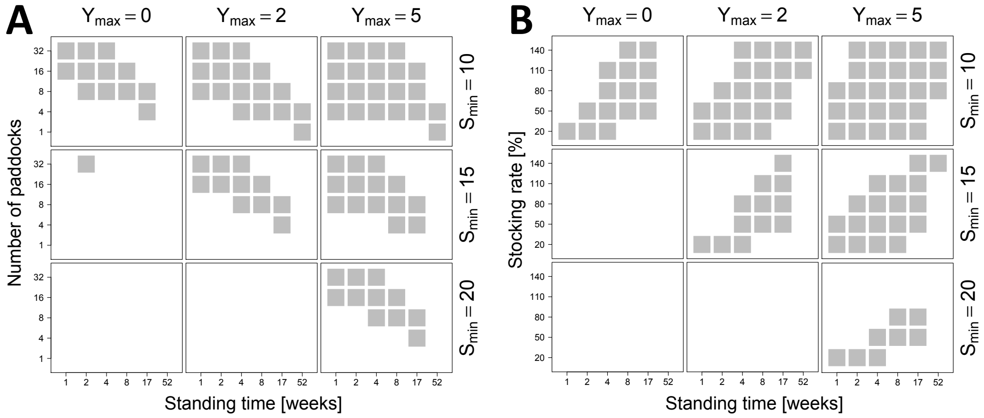


Figure 4.3: Viability space of rotation strategies for different management aims. Strategies are defined to be viable, if 95% of the simulation runs match the objective (indicated by gray squares). The figures shows the changes in the viability space for different minimum incomes ($S_{\min}$) and maximal numbers of years that are manageable to fall below (within 10 years) ($Y_{\max}$) for average climate conditions (R1-V25). (A) Suitable management combinations of paddock number and standing time for a constant stocking rate of 50%. (B) Suitable combinations of stocking rate and standing time on eight paddocks.

suitable for a large range of settings and so most robust: strategies with short standing time and a large number of paddocks. These strategies ensure that the rangeland can regenerate after short-term grazing.

Considering the influence of the stocking rate (Fig. 4.3 B) we observe a similar result. Many strategies are suitable under a low minimum income requirement in combination with a high tolerance to fail this threshold. Again, the range of suitable strategies shrinks with an increasing minimal income requirement and a decreasing tolerance. Here, the combination of high SR and short ST is inappropriate, because it results in a too fast rotation that does not allow sufficient resting periods for the paddocks. Therefore, high stocking rates are not suitable to maintain a high income over a long time. Also, low SR and long ST are inappropriate, because they result in a small herd size and in turn a low income. The most successful strategies are characterised by a medium stocking rate and an appropriate (intermediate) standing time, that allow the paddocks to recover from previous grazing.

4.3.4 Influence of climate change

Finally, we analysed the influence of the scenarios of climate change listed in Tab. 4.2. As far as management objective Obj_1 is concerned, we found that alterations in the distribution of precipitation $LNORM(\overline{r}, \sigma_{\mathrm{r}})$ cause a shift in the functional response of the strategies in terms of mean and CV in the income

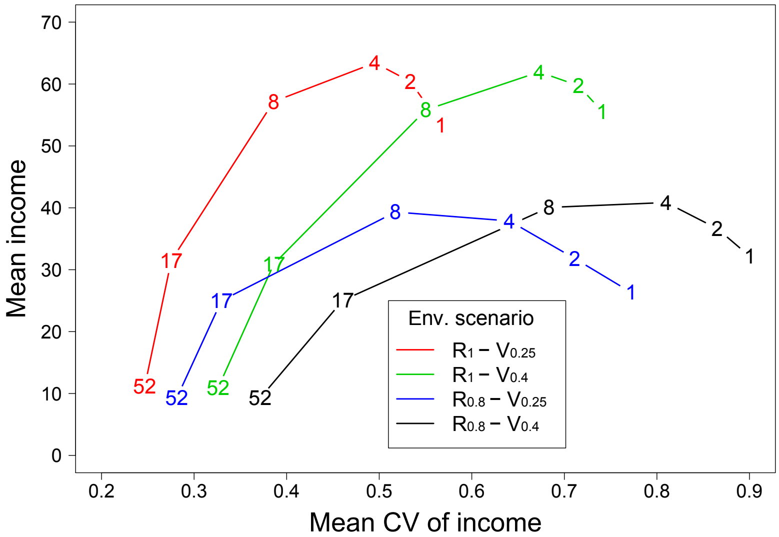


Figure 4.4: Influence of different climatic conditions (Tab.5.3) on the relation between mean ($\overline{S}$) and coefficient of variation (CV) of income. Plotted for different standing times (indicated by the numbers on each curve) on a farm divided into eight paddocks and a stocking rate of 50%.

gained from livestock sales, but did not change the shape of this relationship (Fig. 4.4). All changes to lower $\overline{r}$ and higher σ_r result in an increase in the CV of income. Further, in scenarios with lower $\overline{r}$ the mean income $\overline{S}$ is diminished as a whole.

Fig. 4.5 shows the performance of the management strategies under the same scenarios of climate change from the perspective of management objective Obj_2. Evidently, the climate conditions influence the range of suitable management strategies. A decrease of 20% in the mean precipitation $\overline{r}$ causes a dramatic shrinkage of this range. For example, it is not even possible to achieve a fairly low minimum income S_{min} on a regular basis, regardless of the standing time or the number of paddocks. Also, an increase in the variability of precipitation results in a smaller set of viable options. Again, the more flexible strategies are characterised by an accurate combination of PN and ST, with dominance of a management on many paddocks with a fast rotation. This shows that the climate conditions limit the chance to manage the income risk by appropriately designed adaptive management strategies.

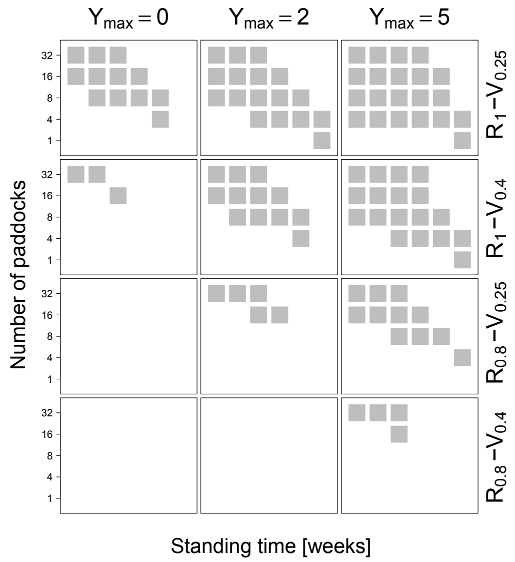


Figure 4.5: Viable management strategies under different climate scenarios (Tab. 5.3) and a defined minimum income of $S_{\text{min}} = 10$. Strategies are defined to be viable, if 95% of the simulation runs match the objective (indicated by gray squares). The figure shows viable combinations under a stocking rate of 50%.

4.3.5 Combining objectives

Both objectives analysed in our study consider a different management aim, but are not mutually exclusive. One reasonable approach for a farmer to choose a management strategy, would be a hierarchical combination of both objectives. First of all, she selects only strategies that secure her livelihood, and therefore suites Obj_2. Secondly, she chooses one strategy out of this set that maximise her mean-CV preference Obj_1 (Fig. 4.6). Alternatively, the farmer could consider other objectives like minimising her working effort.

4.4 Discussion and conclusions

This study uses a generic ecological-economic simulation model to incorporate the feedback between vegetation dynamics in semi-arid rangelands and management activities taken by a livestock farmer. We evaluate different management strategies from the perspective of different management objectives (mean-CV preferences (Obj_1), safety-first approach (Obj_2)), and we assessed the robustness of results against different scenarios of climate change.

The results show that a higher subdivision of the farm combined with an appropriate (and lower) standing time improves the efficiency of a farm enterprise in terms of higher mean income $\overline{S}$, lower CV, and the coverage of a certain min-

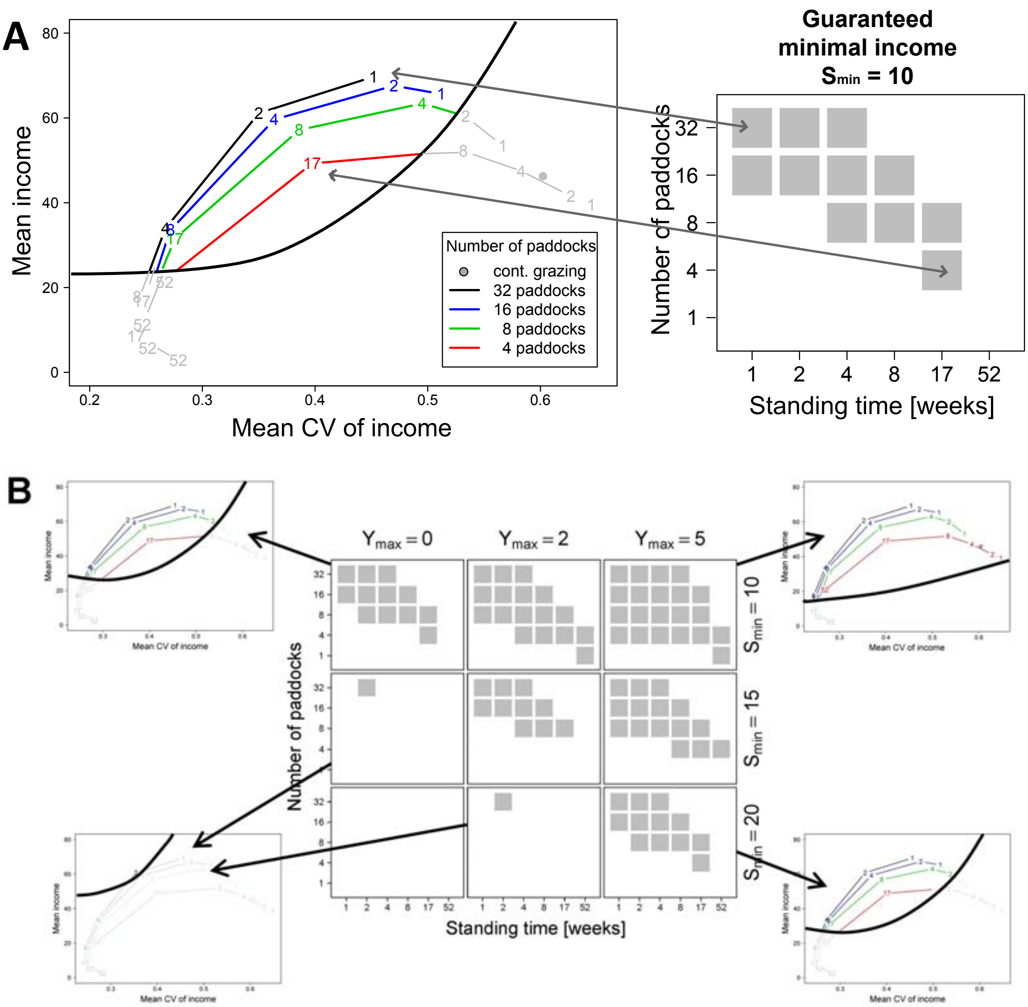


Figure 4.6: Combination of two objectives. (A) Linkage between Obj_1 and Obj_2. Different strategies that meet Obj_2, that means satisfy minimum requirements, can be further evaluated regarding individual mean-CV preferences (Obj_1). The thick black line in the left graph divides the mean-CV-space into viable (upper left) and deficient (lower right) strategies. The arrows exemplarily link identical strategies in the representations of Obj_1 and Obj_2. (B) The requirements of Obj_2 affect the range of viable strategies and therefore, limit the options in the mean-CV-space. The linkage is shown exemplarily for different requirements in Obj_2. The arrows show which limitations in the mean-CV-space result from particular viability ranges.

imum income requirement. This is consistent with the statement of Hart *et al.* (1993) that an intensive rotational grazing system has to be coupled with high pasture subdivision to produce grater livestock pressure and therefore, more uniform grazing. This more homogeneous distribution of grazing in small paddocks (Barnes *et al.*, 2008) is one of the major reasons for the success of a higher number of paddocks in our model, as more cells can be kept close to maximum sustainable yield. Further, we showed that a higher number of paddocks enable to some point a higher stocking rate. Altogether, this supports to some extend the findings of Savory and Butterfield (1998) and Savory and Parsons (1980).

Furthermore, we have found that a whole set of strategies suits the management objective Obj_2. Here, the farmer often has more opportunities than a unique optimal strategy. Nevertheless, the two management objectives (Obj_1 and Obj_2) lead to similar results. We have shown that, whenever the minimum income requirement of the farmer is increasing or economic capacity to tolerate is decreasing, the range of opportunities is shrinking. The most robust strategy that, to a certain extent, stands increasing economic demands as well as decreasing precipitation, is a strategy with short standing time and a large number of paddocks – the strategy that has also been found as promising under management objective Obj_1.

The range of strategies suitable for ensuring minimum income markedly depends on the farmer's economic requirements but also on available resources. For example, a full-time farmer with low abilities (or willingness) to stand bad years depends on a continuous and relatively high income from livestock farming. She has only a few management options and would do best with high degree of subdivision and fast rotation. On the other hand, for a part-time farmer who earns the main income in another job, the farm business may be just extra income. She could set a lower required income and accept a higher variability as she diversified the risk and can buffer low income years. Such a farmer could choose from a large set of strategies, and the selected strategy is likely to depend on other resources. Assuming she has limited time due to the other job she cannot put much effort in an advanced management system and would choose a small number of paddocks, a long standing time, and a low stocking rate.

Further we could show that decreasing mean and increasing variability of precipitation would lead to a reduced set of suitable management strategies. To some degree a farmer can adapt to such changes by adjusting the management system on the farm. However, as functional aspects in rangeland management remain constant regardless of social and economic factors (Connor, 1991), after strong changes the farmer has to scale down requirements, or take other options, such as increasing the farm size or the diversifying the income (Le Houérou, 1996).

A survey conducted for livestock farming in the semi-arid rangelands of Namibia (Olbrich *et al.*, 2009) showed a wide range in expected minimal incomes amongst farmers. Moreover, many farmers are quite flexible to manage falling below this threshold. This is one possible explanation for the huge amount of strategies that are applied in practice. Furthermore one could argue that farmers in semi-arid regions are well adapted to uncertain and risky climate conditions and are possibly to some extend able to adjust there management to climatic changes.

The variety of management options open to farmers in semi-arid areas is virtually unlimited. In this study, we had to restrict the set of strategies that we considered. We assumed an opportunistic stocking strategy with a fixed selling rule. An interesting question for future research would be to assess the performance of other stocking and selling rules (Campbell *et al.*, 2006; Sandford and Scoones, 2006), like a conservative drought avoiding low-stock approach (Walker, 1993) or an adaptive, income driven selling rule. Also, we focused on a constant rotation strategy. To assess the potential of more adaptive rotation strategies that adapt to the current state of the environment (e.g. vegetation, precipitation) is another task for future research. Overall, this would allow comparing the effectiveness of different approaches of risk management and adaptation: approaches focusing on adjusting the rotation and approaches focusing on improving the conditions for destocking and selling. Are both approaches equally effective, or do they differ and when? Answering these questions would further strengthen the knowledge base for the design of the institutional framework for sustainable grazing in semi-arid regions.

This approach takes a quite strong assumption of long-term thinking farmers, which consider a time horizon of 100 years. Furthermore, discounting is not taken into account. This ensures ecological sustainability implicitly, because an effective strategy has to maintain the rangeland permanently in viable condition to yield sufficient income. In contrast, strategies that perform unfavourable on the long term can be economically beneficial, if farmers consider a short time horizon. This would apply for strategies characterised by a huge grazing pressure either caused by too large stock size or too short resting periods per paddock. However, Quaas *et al.* (2007) showed that even myopic farmers will choose a sustainable management strategy as long as their risk aversion is sufficiently high.

In the present study, we did not analyse the costs of rangeland management explicitly. A further step must be the incorporation of production costs and management effort. In this regard, Beukes *et al.* (2002) found a trade-off between ecologically suitability and economically viability at high paddock numbers. The optimal paddock number was depending on annual rainfall. This is likely to apply to the presented results as well, as the increased gain by further doubling in the amount of paddocks is declining for larger paddock numbers (Fig. 4.2 A), while the increase of costs might not decline.

Conclusively, we characterised management strategies that suit risk-averse farmers' objectives and those that are not suitable at all. Although, the optimal management strategy varies widely with management objectives and environmental constraints, our study shows that a relatively high number of paddocks with an adequately high rotation speed appears to be the most robust management strategy. However, it is not suitable to advocate dogmatic a certain kind of management system, as there are plenty different individual needs and goals among livestock farmers.

Chapter 5

How to adapt livestock management to spatio-temporal heterogeneity in semi-arid rangelands?

5.1 Introduction

Management strategies that adapt to environmental variability are expected to prevent degradation of natural resources and ecosystem services (Adger *et al.*, 2005; Walker *et al.*, 2004; Smit and Pilifosova, 2001; Smithers and Smit, 1997). In this regard, the development of flexible land-use strategies that consider essential system properties is vitally important. The need for flexible and well-adapted strategies is particularly high in arid and semi-arid rangelands (Vetter, 2005), which are characterised by highly uncertain and variable climatic conditions. As low and erratic primary production poses the major challenge to extensive livestock farming in such regions, these adapted grazing strategies are supposed to allow an efficient use of scarce resources without running the risk of degradation. Especially the spatial and temporal variability in resource availability has to be taken into account (Vetter, 2005; Schwinning and Parsons, 1999; Westoby *et al.*, 1989). For this reason, timing and spatial distribution of livestock grazing, as well as stocking rate are known as fundamental components in grazing management (Walker, 1995; Heitschmidt and Taylor, 1991). However, the approaches to incorporate these components into management strategies are manifold. They differ in their level of complexity and in particular in the way they are adapted to different system properties. Altogether, there is a need for systematic analyses of the importance of small-scale spatial and temporal variability for suitable management strategies (Beukes *et al.*, 2002; Noy-Meir, 1981) to gain simple and applicable management principles (Ash and Stafford Smith, 1996). Moreover, investigating the relative importance and the interaction effects of different management components of a grazing system (i.e. stocking and rotation rules) is crucial to evaluate their impact on ecological and economic states of semi-arid grazing systems.

Management of semi-arid grazing systems often adapts to the available forage, i.e. the biomass provided by the rangeland. This biomass availability usually varies in space and time (Laca, 2009), as it is influenced by previous and current rainfall and grazing events (Wiegand *et al.*, 2004c; Oesterheld *et al.*, 2001; Skarpe, 1991). Therefore, various kinds of (rotational) grazing systems have emerged (see Tainton, 1999; Heady and Child, 1994; Heitschmidt and Taylor, 1991; Holechek, 1988) to handle the spatio-temporally heterogeneous distribution of primary production. These systems differ in their way to adapt the amount and the spatial distribution of livestock to the given environmental variabilities. First, there exist basically two approaches for an appropriate stocking rule (Campbell *et al.*, 2006; Sandford and Scoones, 2006): (i) non-adaptive, constant rules that aim at maintaining a predefined livestock number and (ii) adaptive (also called opportunistic or tracking) rules that aim at varying livestock numbers to track temporally variable forage supply. Secondly, the spatial distribution of livestock considerably influences primary production. As the biomass availability is usually heterogeneous (Laca, 2009) and grazing itself has an effect on the rangeland condition (Wessels *et al.*, 2007), it is a crucial decision which part of the rangeland is grazed at which time. Respective rotation patterns can either follow a fixed order or adapt to the current rangeland productivity (Vetter, 2005). Regarding the latter adaptive movement patterns are expected to support high livestock numbers even in dry years (Stafford Smith, 1996; Coughenour, 1991). Unlike management decisions on the number of livestock, decisions on the spatial distribution of livestock are usually continuously updated during the year. Although, several authors stress the importance of both management components (Laca, 2009; Vetter, 2005; Walker, 1995; Noy-Meir, 1981), opinions on their practical relevance are contradictory (Brown and Kothmann, 2009; Briske *et al.*, 2008; Campbell *et al.*, 2006; Sandford and Scoones, 2006; Holechek *et al.*, 1999a; Savory and Butterfield, 1998; Illius and O'Connor, 1999). Thus, there is no clear evidence for an advantage of adaptation in either the stocking or the rotation rules. It is hence an open question, which of these two components improves the performance of semi-arid grazing systems more effective and how they interact.

The purpose of this study is to improve the understanding of different rangeland management strategies. We tackle the question, which settings adapt a rotational grazing system best to spatial and temporal heterogeneous resource availability in semi-arid regions in order to maximise the average yield. To this end, we simulate the reaction of a rangeland system to different kinds of management strategies using an ecological-economic model. We focus on different rules of stocking and rotation. Thereby, we highlight the relative importance of these structural elements of semi-arid rangeland systems for an effective risk management and show how different types of adaptability affect the suitability of a management option. Further, we investigate the robustness of different strategies under changing climate conditions, particularly under an increasing degree of uncertainty (i.e. rainfall variability).

5.2 Methods

We apply the full model described in chapter 2 to analyse the impact of rotation and stocking rules on rangeland management performance. The parameter values used for the analyses are listed in Tab. 5.1. Our study considers a set of management strategies that comprises rules of herd rotation, and stocking rules differing in their degree and type of adaptability.

Table 5.1: Model parameters

parameter	value	description
$S_{\max}$	2500	maximum amount of storage biomass
m_{S}	0.04	respiration rate of storage biomass
m_{B}	0.0095	decomposition rate of brown biomass
ρ_1	0.0	minimum required rainfall for growth
ρ_2	2.3	required rainfall for maximum growth $g_{\max}$
$g_{\max}$	0.52	maximum growth rate of green biomass
$a_{\max}$	0.111	maximum storage transfer rate
τ_{S}	0.02	upper threshold of storage support for green biomass growth
τ_{G}	0	lower threshold of green biomass below which storage is not replenished
ψ	0.9	preference of livestock for green biomass
α	0.96	conversion rate from storage to green biomass
β	0.191	conversion rate from green to storage biomass
$\mu_{\max}$	1.33	maximum annual growth rate of livestock
$H_{\max}$	[0, 500]	intended stock size for constant stocking
ν	[0, 200]	relative stocking rate for adaptive stocking

5.2.1 Management strategies

Spatial farm structure

The modelled rangeland is subdivided into 16 paddocks, each consisting of 64 grid cells. This arrangement is identical for all simulations in this study.

Rotation rules

Most livestock ranches in semi-arid areas apply one of various kinds of rotational grazing schemes. That means the farmland is subdivided into multiple paddocks, and grazed in rotational sequence allowing recovery of rested areas. Thereby, the herd is shifted from one paddock to the next after a certain period of time. In the model, the livestock grazes all available aboveground biomass on one paddock before it is shifted to another one according the rotation rule applied. We compare one non-adaptive and four different adaptive rotation rules of paddock selection (Tab. 5.2). The non-adaptive selection of the next paddock (NAR) follows a fixed sequence. Thereby always the paddock that had the longest resting period is grazed next. The four adaptive rules select the next paddock depending on the paddocks' conditions, with two of them additionally distinguish between rainy and dry season. The adaptive rotation rule AR_{AB} selects always the paddock with the highest amount of aboveground biomass (ABM) to be grazed next. In the adaptive rule AR_{SB} the livestock moves always to the paddock with the highest amount of storage biomass (SBM) that provides any ABM. The two other adaptive rules differentiate between rainy and dry season when adapting to the amount of ABM (SAR_{AB}) or SBM (SAR_{SB}), respectively. These rules choose only in the rainy season the paddock with the most ABM/SBM. In the dry season particularly paddocks with low amount of ABM/SBM are grazed.

Table 5.2: Implemented livestock management rules.

	Rule	Description
NAR	Non-Adaptive Rotation	fixed paddock sequence for livestock rotation
AR_{AB}	Adaptive Rotation to Aboveground Biomass	always paddocks with highest ABM are grazed
SAR_{AB}	Seasonal Adaptive Rotation to Aboveground Biomass	in rainy season paddocks with highest ABM are grazed – in dry season paddocks with a low ABM are grazed
AR_{SB}	Adaptive Rotation to Storage Biomass	always paddocks with highest SBM are grazed
SAR_{SB}	Seasonal Adaptive Rotation to Storage Biomass	in rainy season paddocks with highest SBM are grazed – in dry season paddocks with a low SBM are grazed
NAST	Non-Adaptive STocking	constant stock size – fixed intended number of livestock
AST	Adaptive STocking	opportunistic stocking – stocking rate depends on the amount of ABM

Stocking rules

We compare two stocking rules differing in their degree of flexibility (Tab. 5.2). The first one is a non-adaptive (continuous) stocking rule, where the farmer aims for a fixed number of animals $H_{\max}$ on the farm in every year. This number remains constant, regardless of any changes in the state of the ecosystem. The second one is an adaptive (also called opportunistic or tracking) stocking rule. Here, the farmer varies the maximum number of livestock according to currently available forage supply M each year at the beginning of the dry season: the stocking rate ν corresponds to a fixed percentage of available forage that should be used. Stocking rates of more than 100% can be reasonable, because new biomass will be produced during the year within the next rainy season. Hence, the maximum number of livestock $H_{\max}$ for each year y is given by:

$$H_{\max,\,\mathrm{y}} = \begin{cases} H_{\max} & \text{constant stocking (NAST)} \\ \frac{\nu \cdot M_{\mathrm{y}}}{100} & \text{adaptive stocking (AST)} \end{cases} \tag{5.1}$$

For both strategies the farmer sells the surplus of animals that exceed the calculated herd size. We further assume that only own animals are raised and livestock is never purchased.

5.2.2 Ecological-economic evaluation of management strategies

In order to evaluate the different management strategies in terms of their appropriateness and to provide insight into the importance of adaptiveness in management decisions, we observe criteria of ecological and economic sustainability: the ecological criterion is the state of the ecosystem is characterised by the amount of storage biomass (the vigour of the pasture). The economic criteria are the number of sold livestock and the herd size that can be supported on the farm.

5.2.3 Simulation settings

We define different rotational grazing strategies by combining all rotation and stocking rules (see Tab. 5.2). For the non-adaptive stocking rule we apply a range of fixed intended livestock numbers from zero to 500 LSU. The adaptive stocking rule applies stocking rates ν that aim to use a certain fixed percentage of the available ABM each year varying between zero and 200 percent. All analyses are executed for one scenario with constant precipitation and two stochastic scenarios with a variance in rainfall of 0.1 and 0.25, respectively (see Tab. 5.3).

Table 5.3: Parameters of climate scenarios.

Scenario	Mean rainfall $\bar{r}$	Variance of rainfall σ_r	length of rainy season	Description
Constant	1	0	18 weeks	constant rainfall with a fixed length of the rainy season
Stochastic 1	1	0.1	15-21 weeks	stochastic rainfall with low variance and variable length of the rainy season
Stochastic 2	1	0.25	15-21 weeks	stochastic rainfall with high variance and variable length of the rainy season

We simulate all management strategies for a period of 200 years. For the stochastic climate scenarios the simulations are repeated 100 times with different stochastic precipitation. All simulations start with an initial storage biomass of 80% of the maximal carrying capacity and an initial herd size of 50 LSU. We used the first 100 years as a stabilisation phase and evaluated the mean number of sold livestock, herd size and storage biomass from the following 100 years for the analyses.

In the following, we use the storage biomass at the beginning of the dry season as an indicator for the ecological condition and the herd size or the amount of sold livestock as an indicator for economic condition of the farming system, respectively. First, we explore the behaviour of the selected strategies in a stable environment, i.e. under constant precipitation. Subsequently, we test the robustness of these results under variable climatic conditions.

5.3 Results

Management strategies in rotational grazing systems differ in their level of complexity and adaptivity. Different components of such grazing systems are expected to allow for adaptation to environmental heterogeneities in space and time. Overall, we investigate whether it is important to apply an adapted rangeland management and if so, which traits characterise a successful strategy.

5.3.1 Performance of management strategies in a stable environment

In this section we analyse the behaviour of the different strategies under the same constant precipitation in every rainy season. The application of non-adaptive stocking rules generally causes threshold behaviour regardless of the particular rotation rule applied (Fig. 5.1 A): the mean herd size increases with the intended stock size up to a certain critical value. Above this threshold the rangeland cannot support the targeted livestock number and the herd size collapses to zero. This threshold value can be interpreted as the stock size where the system can produce the maximum sustainable yield. The magnitudes of optimal stock size and maximum yield are determined by the specific rotation rule.

In detail, the adaptive rules $\mathrm{SAR_{AB}}$ and $\mathrm{SAR_{SB}}$ that adapt the rotation to the rangeland quality and apply different rules in the rainy and in the dry season produce the highest mean livestock number. Here, the rule $\mathrm{SAR_{AB}}$ that adapts to the rangeland quality in terms of aboveground biomass (ABM) performs slightly better than the rule $\mathrm{SAR_{SB}}$ that is guided by the storage biomass (SBM). Both adaptive rules outperform the non-adaptive rotation rule (NAR), which rotates the livestock in a fixed order. However, not every kind of adaptation improves the maximum yield. Rules that only adapt to the best rangeland quality while ignoring the season of the year have even a lower threshold than the NAR rule. Here again a strategy that adapts to the SBM ($\mathrm{AR_{SB}}$) yields a lower mean herd size than the strategy that chooses always the paddock with the highest ABM ($\mathrm{AR_{AB}}$).

This performance directly translates to an economic value, the number of mean livestock sales (Fig. 5.1 B). It is clearly visible that the applied trading rule of selling all animals that exceed the intended stock size leads to mean livestock sales that follow the mean herd size proportionally. This indicates that the reproduction rate is constantly on a maximum value as long as the intended stock size lies beyond the threshold.

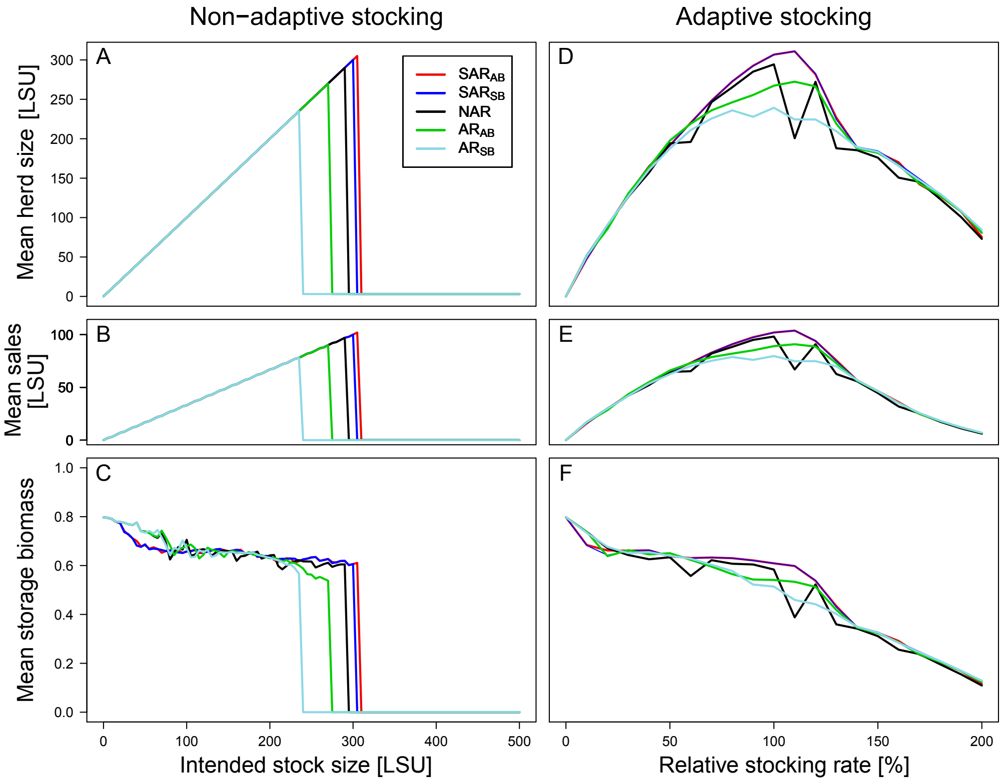


Figure 5.1: Mean herd size (A & D), livestock sales (B & E), and storage biomass (C & F) for the different management strategies (Tab. 5.2) over 100 years under constant precipitation. (The curves of rules SAR_{AB} and SAR_{SB} under adaptive stocking (D – F) are largely similar and overlay each other.)

The mean storage biomass (i.e. rangeland quality), exposes the underlying mechanism of the described behaviour (Fig. 5.1 C). The dynamic is driven by a negative feedback between herd size and storage biomass. A high intended stock size aims at maintaining a large herd size that in turn reduces the amount of storage biomass. If the stock size exceeds the threshold the grazing pressure is too high to allow sufficient recovery of the storage biomass and consequently, the rangeland condition decreases to a level that cannot support livestock grazing anymore. The response of the mean storage biomass to the intended stock size is largely similar for the different rotation rules (Fig. 5.1 C). However, it differs slightly when approaching the critical intended stock size. For most of the rotation rules the mean storage biomass crashes abruptly at the individual threshold, whereas the rule AR_{AB} exhibits a slight decrease in storage biomass already at intended stock sizes below the threshold. Moreover, at a small range of very low intended stock sizes the mean storage biomass of the rules SAR_{AB} and SAR_{SB}

falls below the values of the rules NAR, AR_{AB} and AR_{SB}, without having a negative impact on the herd size and the amount of livestock sales.

In summary, for a non-adaptive stocking rule (Fig. 5.1 A – C) only rotation rules that account for seasonality and pasture quality perform better in terms of ecological and economic values than a non-adaptive rotation rule. On the other hand, the rotation rules that adapt to the best pasture quality alone perform even worse.

For the adaptive stocking rules (Fig. 5.1 D – F), the behavioural response differs significantly to those observed for non-adaptive stocking rules (Fig. 5.1 A – C). Tracking the adequate livestock number depending on the current condition of the rangeland makes the management strategies more robust against too high targeted stocking rates. At low grazing pressures the mean herd size increases continuously with the applied stocking rate. If this stocking rate exceeds the optimal value, a negative response in the rangeland condition leads to a reduction in the herd size and in turn in the sold livestock. However, there is no threshold for the stocking rate, above that the rangeland system would crash abruptly. Even at high stocking rates livestock sales are still achieved. However, in this case the mean number of sold livestock decreases faster than the mean herd size.

The different rotation rules respond similar under the adaptive stocking rule compared to the non-adaptive stocking rule. The rules SAR_{AB} and SAR_{SB} outperform the other rotation rules. In particular under a medium stocking rate they lead to considerably higher mean herd sizes, livestock sales, and rangeland conditions.

The results under the non-adaptive rotation rule NAR are partly similar to those under SAR_{AB} and SAR_{SB}, but certain medium stocking rates are detrimental to livestock production and rangeland condition (Fig. 5.1 D – F).

This is due to a synchronisation of the paddock order and the seasons of the year. Basically the same paddocks are grazed at the same season each year. Hence, some paddocks are always grazed during the rainy season until their storage is heavily reduced. This synchronisation is caused by the combination of a fixed rotation order with a particular herd size resulting in a particular detrimental standing time per paddock.

Also for adaptive stocking, the rotation rules AR_{AB} and AR_{SB} perform worse than SAR_{AB} and SAR_{AB} under medium stocking rates (Fig. 5.1 D – F). When compared to NAR they are also unfavourable for most stocking rates, but, however, appear to be more predictable and robust against accidental collapses at certain stocking rates.

Summing up, adaptive stocking is more robust against overestimations of the optimal herd size than non-adaptive stocking. Furthermore, the rotation rule is an important tool to increase the achievable return from livestock sales. However, not every kind of adaptation is beneficial for an improvement of a management strategy.

5.3.2 Spatio-temporal effects of grazing management in a stable environment

So far, we analysed the response of a rangeland system to the different management strategies on the aggregated farm level. We learned which strategies can produce higher average yields than others and how they respond to different grazing pressures. To gain a better understanding why certain strategies produced the patterns observed, we now investigate the spatio-temporal rangeland dynamics and underlying principles in more detail. To this end, it is important to understand how single paddocks are utilised under the different strategies over time. The following section explains the basic impact of grazing at different times of the year and elaborates its consequence for rangeland quality. Thereafter, we examine how single paddocks are utilised under different management rules and how this leads to the observed pattern on the landscape scale.

Rangeland response to grazing

The impact of grazing on the rangeland condition is based on the intra-annual interaction between storage and green biomass (see chapter 2.2.7 for details). In the beginning of the rainy season the storage biomass invests energy to support the initial growth of new green biomass. In the course of the rainy season the accumulating green biomass more and more replenishes the storage. The impact of this process is largest at the end of the rainy season. Therefore, a complete removal of the green biomass during the rainy season diminishes the potential for regenerating the storage biomass and initiates a further investment of the storage. In contrast, in the dry season, there is no interaction between storage and aboveground biomass. Thus defoliation in the dry season has no negative impact on the storage biomass. Consequently, grazing has a harmful effect on the rangeland condition in the rainy season, while it is harmless in the dry season.

Hence, the damage of the storage depends on the time of the year in which a paddock is grazed. Furthermore, the grazing pressure and the duration of defoliation are important determinants for the degree of storage degradation. If the grazing pressure is large and a paddock is grazed for a long period during the rainy season, the storage biomass is seriously diminished. In contrast, the same grazing event during the dry season has no impact on the paddock's storage condition. Accordingly, a paddock has to be rested during the rainy season to improve the range condition, but can be utilized in the dry season.

For all investigated strategies the standing time on one paddock emerges endogenously from the amount of grazeable biomass on this paddock. The livestock consumes all aboveground biomass of one paddock before it moves on. Thus, paddocks in good conditions that have not been grazed for at least one rainy season and, consequently, accumulated a huge amount of aboveground biomass allow a long standing time.

Yet, how do standing time and season of grazing interact with different paddock conditions? Paddocks in a good condition produce more aboveground biomass in one year, than paddocks in a bad condition and, therefore, provide a large proportion of the forage supply. However, if they are not grazed in the dry season they preserve most of the forage for the next rainy season. Then, they offer enough forage for a very long standing time which in turn causes a strong degradation of the storage biomass. In contrast, a “good” paddock that was grazed in the dry season, provides only little forage in the beginning of the next rainy season and can be grazed only for a short time. This effect applies also to paddocks in medium condition, but the possible standing time is correspondingly lower. On the other hand, the storage can be recovered on paddocks that are not grazed during the rainy season

These processes are particularly important in a rotational grazing system, where the livestock is systematically moved between different paddocks, to allow an adequate spatial and temporal distribution of the grazing pressure over the whole farm. In our study one single paddock is grazed by the entire herd for a certain period of time, while the other paddocks are rested and can recover from previous grazing events. In such a grazing system an increasing herd size speeds up the consumption of the available forage on one paddock. This decreases the standing time on each paddock and in turn the resting time for the other paddocks. The herd returns too fast and a grazed paddock cannot regenerate sufficiently. If this happens to all paddocks’ the whole farm will permanently degrade on the long run.

Functioning of the rotation rules

In this section we focus on the basic functioning of the different rotation rules. To this end, we use the storage biomass after the rainy season as an indicator for rangeland condition, because it provides the basis for livestock grazing. First, we investigate the functioning of the rotation rules under non-adaptive stocking in detail. Second, we do the same for adaptive stocking and compare the results.

Non-adaptive stocking The non-adaptive rotation rule NAR results in a sequential spatio-temporal pattern of paddocks with diminished storage biomass (Fig. 5.2 A1 – A4). The formation of this pattern is changing depending on the stock size. If the herd size is low enough to provide sufficient time for resting, the number of paddocks in a good condition is high (Fig. 5.2 A1 – A3). However, with increasing stock size the grazing pressure on the pastures becomes too high. Beyond a certain threshold value of the stock size, the paddocks are not able to recover from the past grazing events, which results in a depletion of all storage biomass (Fig. 5.2 A4).

This pattern arises from the rotation rule: in NAR rule the paddocks are grazed in a fixed sequential order. As an outcome, the livestock grazes always the

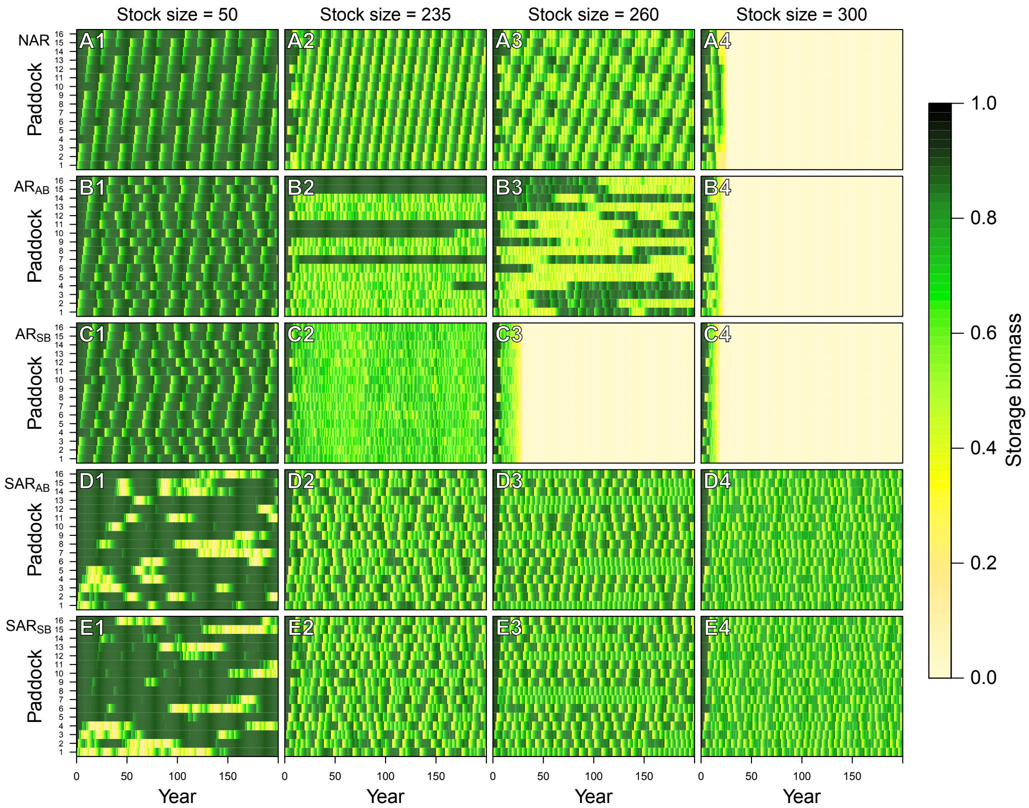


Figure 5.2: Spatio-temporal pattern of storage biomass for different rotation rules (Tab. 5.2) and stocking numbers. The figure shows the results for non-adaptive stocking under constant precipitation. The storage biomass ranges from 1 (excellent) to 0 (degraded).

paddock that was rested for the longest time. However, the individual grazing time per paddock emerges endogenously from the stock size. Thus, the season of utilisation is not controlled by the rotation rule. Consequently, every paddock can be grazed in the rainy season regardless the storage condition. Eventually, this fixed rotation order leads to a complete degradation of all paddocks.

The adaptive rotation rule AR_{AB} tries to overcome this problem, as it chooses always the paddock with the best aboveground biomass (ABM) to be grazed next (Fig. 5.2 B1 – B4). At first sight, this rule could be expected to be beneficial to the rangeland condition. However, it actually supports a lower maximum herd size than the NAR rule (Fig. 5.1 A). Particularly, at critical stock sizes we observe two generally different cases of paddock behaviour (Fig. 5.2 B2 & B3 and Fig. 5.3 B1): on the one hand, there are paddocks that continuously stay in a good condition. On the other hand, there exist paddocks whose condition alters between a medium and a low stage. This is reflected by a bimodal frequency distribution (Fig. 5.3

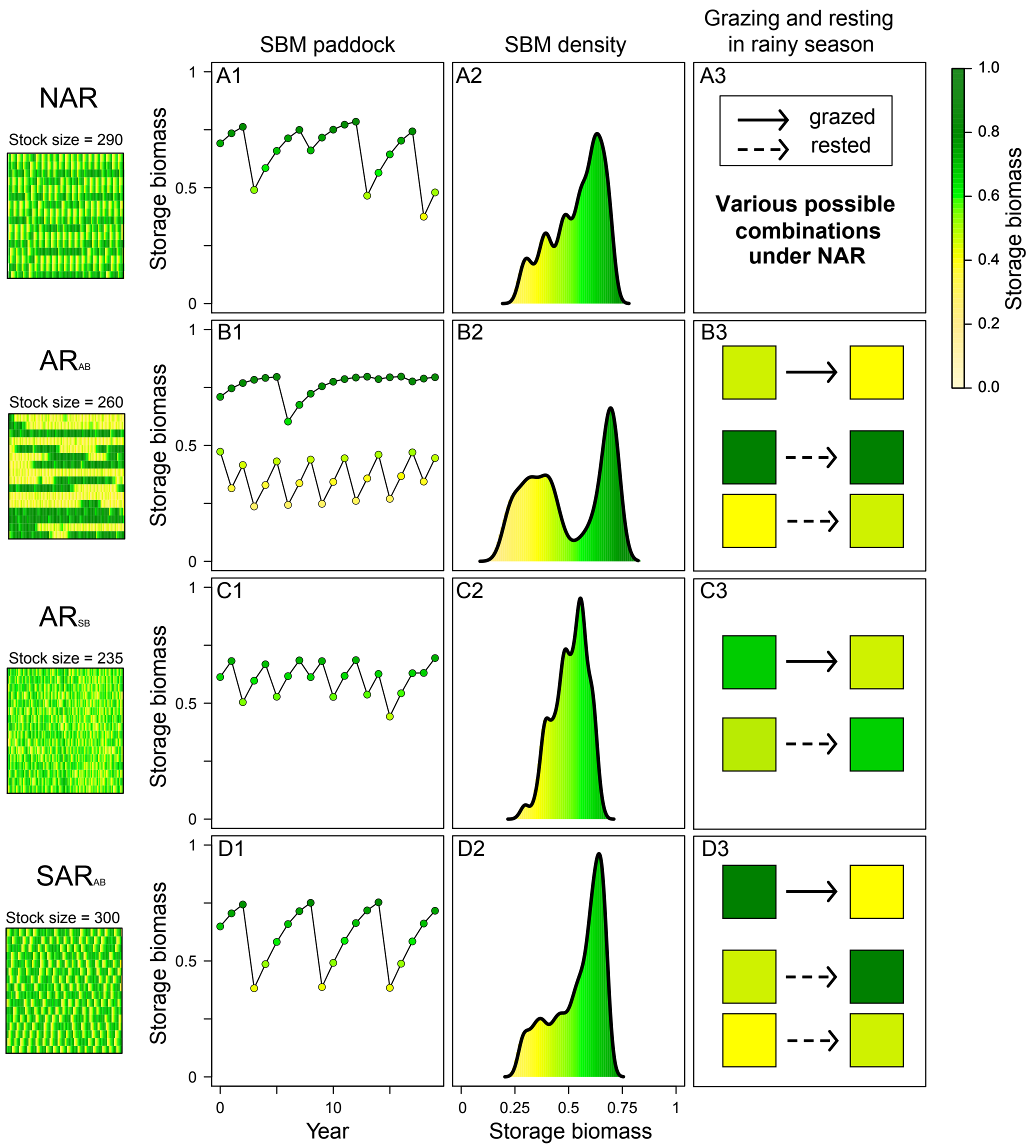


Figure 5.3: Influence of non-adaptive stocking under the rotation rules NAR, AR_{AB}, AR_{SB}, and SAR_{AB} on the rangeland condition. The graphs show the storage biomass at the end of each rainy season on a scale from 1 (excellent - dark green) to 0 (degraded - beige) as an indicator for rangeland condition. The rangeland conditions are illustrated as (1) temporal dynamics on representative paddocks, (2) density of conditions over all paddock during 100 years, and a schematic representation of (3) typical paddock utilisation and dynamics in rainy and dry season. For each plot the stock size is chosen just below the individual critical threshold of each strategy.

B2) of the storage biomass composed of a few paddocks in good condition and others with medium to low storage biomass. This distribution stays more or less stable if the grazing pressure is low enough to maintain some "good" paddocks (Fig. 5.2 B2 & B3). However, if the stock size is too high all paddocks degrade successively within a few years (Fig. 5.2 B4).

This pattern is caused by the seasonal use of the paddocks that emerges endogenously from the rotation rule (Fig. 5.3 B3). The "good" paddocks, which normally hold the highest amount of ABM after the rainy season, are primarily used during the next dry season. Therefore, the paddocks in medium and low conditions stay ungrazed until the following rainy season. Then, the paddocks in a medium condition have the highest ABM and are grazed with a medium standing time. This results in the degradation of their storage. Mostly, the paddocks with the lowest storage biomass remain ungrazed and can recover to a medium stage. Beyond a critical stock size, however, the medium paddocks are insufficient to bridge the whole rainy season and the paddocks in a good condition were used additionally. This results in a successively degradation of the whole farm. As this rule still neglects the intra-annual seasonality it decreases the recovery potential of the rangeland and performs worse than the non-adaptive rotation rule NAR.

In contrast, the rule AR_{SB} moves the livestock always to the paddock with the best storage condition (if any ABM is available). This avoids the resting of the good paddocks in the rainy season, and enables the inferior paddocks to recover. Nevertheless, as we learned in section 5.3.1 this rule results in the lowest maximum yield.

If we look at single paddocks, we observe more or less homogeneous rangeland conditions over time (Fig. 5.3 C1). Towards the maximum sustainable stock size this strategy leads to a smaller range of observed paddock conditions compared to the other strategies (Fig. 5.3 C2). The whole farm is in a largely homogeneous condition (Fig. 5.2 C2). However, none of the paddocks is in excellent condition. The rule AR_{SB} is vulnerable already at a comparatively low stock size (Fig. 5.2 C3 & C4).

In this strategy, always the paddocks with a higher amount of storage biomass are grazed (Fig. 5.3 C3). Hence, they loose all aboveground biomass in the dry season. As the ratio in storage biomass between the paddocks does not change during the dry season, these paddocks are also used first when new green biomass emerges in the rainy season. However, as these paddocks have already been grazed in the previous dry season the amount of available forage and therefore the standing time is low. This results only in a minor damage of the storage biomass. Nevertheless, paddocks in a lower condition cannot recover completely before they are harvested again. Hence, there are no paddocks in good condition that can buffer an increasing grazing pressure and allow a sufficient resting time for other paddocks. Consequently, all paddocks are more or less coevally overused and the rangeland collapses at comparably low herd sizes.

To incorporate the seasonality explicitly, the rotation rules SAR_{AB} and SAR_{SB} apply a different stocking rule in the rainy season than in the dry season. Both rules operate on the same principle and are similar in their performance.

The differentiation between the seasons, clearly improves the rangeland management. On the farm scale a spatially as well as temporally heterogeneous pattern of paddocks emerges, that covers the whole range of different pasture conditions (Fig. 5.2 D2 – D4 & E2 – E4). Thereby, even at a large stock size most of the patches are in a good condition, while only a few are in a suboptimal condition (Fig. 5.3 D2). However, a prolonged negative impact on the vegetation condition appears on some paddocks at low stocking numbers (Fig. 5.2 D1 & E1). This effect has no negative impact on the survival of the livestock, and disappears for medium and high livestock numbers (Fig. 5.1 A & B). In these strategies, the paddocks in medium and low conditions are only grazed in the dry season, when defoliation is harmless. The few paddocks in very bad condition for low stocking numbers can be explained as follows: in the dry season the livestock is moved to a paddock in a bad condition and remains on this paddock until all aboveground biomass is grazed. In the rainy season the storage biomass of this paddock is etiolated, because the growth of new green biomass is continuously supported by the storage biomass, but never grazed completely due to the low stock size. The reason of the good performance of these strategies at larger livestock numbers is the utilization of the good paddocks only in the rainy season (Fig. 5.3 D3). As they hold a huge amount of ABM, the standing time is long and therefore the number of grazed paddocks in one season low. Thus, very few paddocks are heavily damaged. However, this allows all other paddocks to recover. In the next rainy season other paddocks are used, while the previously degraded paddocks are rested. It turns out that this distinct cycle of heavy utilisation and long resting (Fig. 5.3 D1) facilitate an effective rangeland management, because it enables the full recovery of damaged paddocks up to a comparably high stock size.

Adaptive stocking The application of an adaptive stocking rule prevents an extensive degradation of all paddocks (Fig. 5.4). None of the rotation rules causes a complete collapse of the management system within a broad range of intended stocking rates. Nevertheless, compared to a non-adaptive stocking the general behaviour of the different rotation rules holds also true under adaptive stocking. Likewise under the non-adaptive stocking the rules form their distinct spatial and temporal pattern of different rangeland conditions. They are observed over a broad range of stocking rates (Fig. 5.4 1A – 4E). However, if the optimal stocking rate is exceeded, we observe a stronger increase in the number of paddocks with lower storage conditions and the conspicuousness of the pattern attenuates (Fig. 5.4 A5 – E5).

Furthermore, under certain stocking rates the non-adaptive rotation rule NAR temporally degrades large parts of the rangeland (e.g. Fig. 5.4 A3). This results in much lower mean livestock sales (Fig. 5.1 E1 – E5). This effect is caused by the

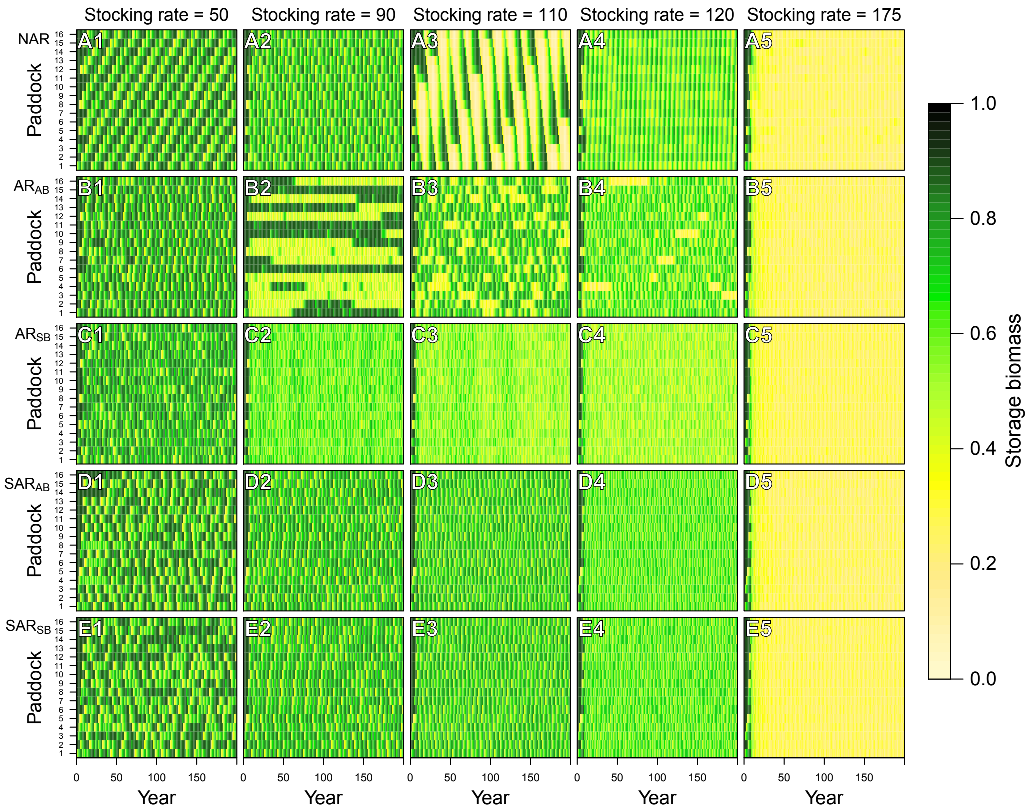


Figure 5.4: Spatio-temporal pattern of storage biomass for different rotation rules (Tab. 5.2) and stocking rates. The figure shows the results for an adaptive stocking rule under constant precipitation. The storage biomass ranges from 1 (excellent) to 0 (degraded).

synchronisation of grazing events on certain paddocks at a similar time each year. More precisely, the same paddocks are constantly grazed each rainy season until the storage almost completely disappeared. Only the adaptation of the livestock number to the current rangeland condition prevents the collapse of all paddocks and the damaged paddocks can recover.

5.3.3 Robustness of strategies in a stochastic environment

In this section we analyse the flexibility of the different strategies and investigate if their behaviour is robust under a stochastically fluctuating rainfall.

The performance of all strategies in a stochastic environment is similar to their performance in a stable environment (Fig. 5.5). Again, for the non-adaptive stocking rule (Fig. 5.5 A – C) we observe a collapse in the mean herd size, the mean livestock sales as well as the mean storage biomass when the optimal stock size is exceeded. However, the exact location of the threshold can not be predicted precisely, because of the stochastically fluctuating precipitation. Moreover, the rangeland system does generally not collapses immediately above the threshold, but persists at lower levels of all system variables for some higher stock sizes. Furthermore, the mean optimal stock size is deceased in a stochastic environ-

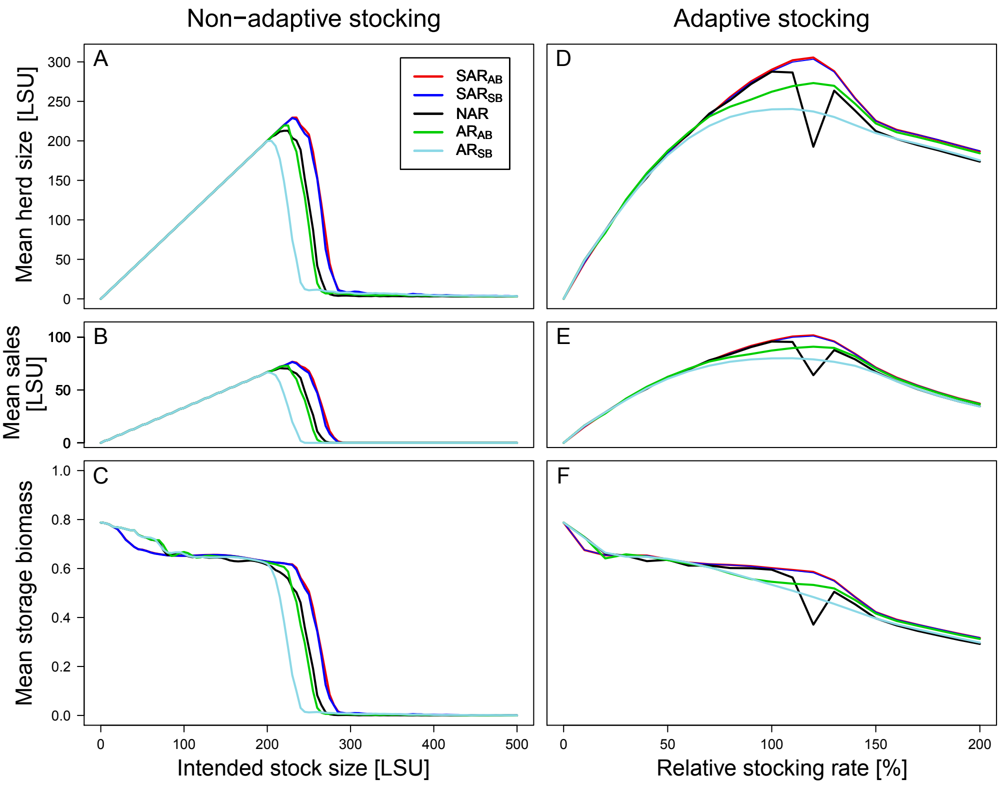


Figure 5.5: Livestock sales (B & E), herd size (A & D), and storage biomass (C & F) for all different management strategies (Tab. 5.2) and under stochastic precipitation with low variance ("Stochastic 1"). Graphs show the mean values of 100 years and 100 simulation runs. (The curves of rules SAR_{AB} and SAR_{SB} under adaptive stocking (D – F) are similar and overlay each other.

ment compared to a stable one. This is reflected in a decreasing amount of maximum possible mean livestock sales with increasing stochasticity (Fig. 5.6). Even the uppermost possible mean livestock sales of all simulation runs of both analysed precipitation scenarios undermatches the mean livestock sales in a stable environment. Furthermore, the non-adaptive rotation rule NAR is more fragile to stochastic conditions. In contrast to all other rules its performance decreases stronger with increasing fluctuations. This is the consequence of the absence of any possibility to adapt to the stochastic climate conditions.

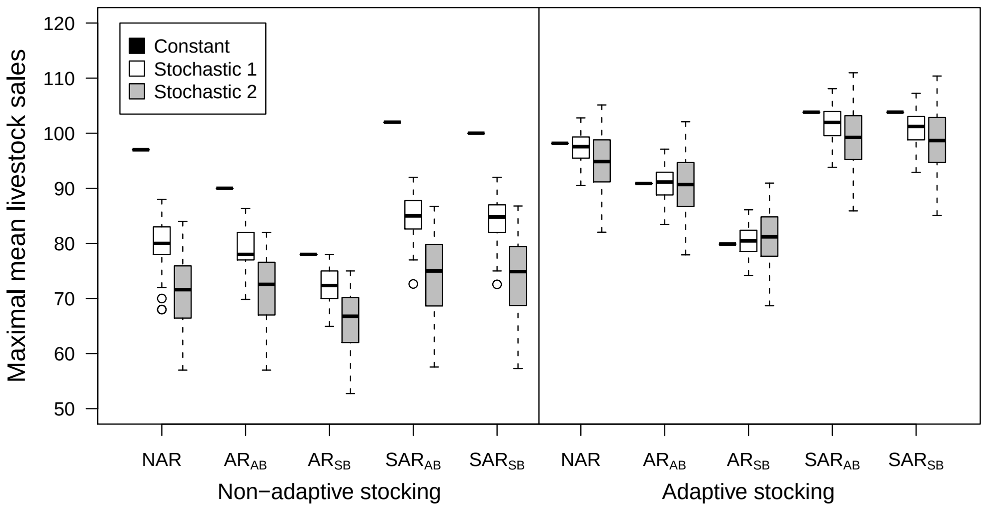


Figure 5.6: Maximum amount of mean livestock sales for all management strategies (Tab. 5.2) under different precipitation scenarios (Tab. 5.3). The boxplots represent the mean livestock sales of the 100 simulation.

The results for the adaptive stocking rules are mostly similar under constant and stochastic precipitation (Fig. 5.5 D – F). Thereby, the maximal mean herd size and therefore the maximal mean number of sales vary slightly for the different simulation runs (Fig. 5.6). There are even some beneficial runs where the stochastic environment leads to a higher mean herd size. Additionally, in a stochastic environment the long term response of the rangeland system to very high stocking rates is less negative. This is a consequence of unscheduled resting phases after low rainfall years. Here, the low rainfall results in a low amount of grazeable biomass. If the herd size is now larger than the available forage it is reduced due to livestock sales. If this event is followed by years with a higher amount of precipitation, the availability of ABM is much bigger than the demand of the remaining livestock and the pastures have the possibility to recover. This recovery leads to a higher mean storage biomass and enables to keep a larger number of livestock on the long run.

In summary, the functional behaviour of the different strategies is generally robust against fluctuations in rainfall. However, stochastic fluctuations in the rainfall reduce the mean economic return, under the non-adaptive stocking rule. Furthermore, the ranking of all different rotation rules persists in a stochastic environment except for the NAR rule under the non-adaptive stocking rule. This strategy falls of in quality compared to all other strategies, because it is not capable to adapt adequately to the stochastic variability.

Spatial effect of stochastic precipitation

The behavioural pattern described for the stable environment (see section 5.3.2) can be observed under stochastic conditions as well (results not shown). However, they could not be detected as obvious as under constant conditions, because it is overlaid by the response of the farming system to fluctuating rainfall.

5.4 Discussion

Semi-arid rangelands are characterised by different types of environmental variability (e.g. temporal variability of precipitation, spatio-temporal variability of resource availability, and non-linear resource production due to seasonal variability). Grazing management has to cope with such variabilities to foster sustainability. However, there are various possibilities to adapt rangeland management to environmental variability: e.g. through adapting stocking or through adapting rotation. The relative importance and combined effects of these two variants were not fully understood so far. Therefore, we consider a range of grazing strategies combining different degrees of adaptiveness in stocking and rotation, and compare them regarding their performance under different degrees of climate stochasticity.

As one of the main results, the stocking rule is more important for the performance of the grazing strategy over a large range of climate conditions than the rotation rule. This supports general statements of Holechek *et al.* (1998) and Walker (1995), who claim that stocking is the most important variable in grazing management. Thereby, the major difference between the non-adaptive and the adaptive stocking rule is that the sharp breakdown beyond an optimal stock size in the non-adaptive case is replaced by a smooth gradual decline above the optimal stocking rate in the adaptive case.

Furthermore, the herd size (either defined by constant stock size or adaptive stocking rate) controls whether fine structure and type of adaptation of the rotation rule have influence on the performance of the grazing strategy. In the case of either low or high stocking numbers, all rotation rules were found to have similar effects. Hence, there is no need for extra-adaptiveness in the rotation rule, as the impact of the stocking rule is dominant. In contrast to low or high stocking numbers, the spatial element of the grazing strategy becomes important in the economically most interesting range around the optimal stocking number. Here, the type of rotation is an essential tool to influence the maximum achievable mean biomass, herd size and return from livestock sales. Appropriate adaptation to spatial environmental heterogeneity thus leads to a larger mean yield.

However, adaptation does not automatically lead to an improvement of the performance. Inappropriate adaptation can also lead to deterioration. In this study, for example, adapting the rotation rule to the best available forage or storage conditions was found to diminish the performance of grazing management, whenever the seasonal variance of semi-arid rangelands was neglected. The lowest performance was found for the adaptation rules “go always to the paddock with the highest storage / green biomass”. In this regard, we challenge the findings of Ward *et al.* (2004), who suggested to move the livestock wherever there is the most grass as best strategy. We found that adaptive rotation does only lead to an improvement if it accounts for both spatial heterogeneity in paddock quality and seasonality. Only this ensures maintaining regeneration ability of the overall rangeland up to a large grazing pressure, because it implicitly provides sufficient resting periods to parts of the rangeland. In this regard, a study of Müller *et al.* (2007) showed that also explicit planning of resting phases can lead to improvement of rangeland quality.

Our model results indicate that the ranking order among different rotation rules is insensitive to the stocking rule, but changes with an increasing degree of climate stochasticity. Here, the non-adaptive rotation rule worsens its performance more than all other rules, because it is not able to buffer the variability in precipitation by spatial adaptation to the paddock quality. Overall, there is a higher variance of optimal mean livestock sales in more variable environments and therefore, a higher risk of income loss or even of a collapse of the whole rangeland under a non-adaptive stocking rule. These findings are supported by Schwarz (2004), who found that, in stochastic environments, an increasing targeted harvesting rate increases the risk of an early breakdown of a rangeland system. However, we can show that in comparison to this rather simple modelling approach that does not allow any management improvement, an adaptation to spatio-temporal heterogeneities can attenuate and in case of adaptive stocking even avoid the risk of a complete breakdown under high grazing pressure.

Generally, also the functional response of stocking rules is robust against stochasticity. Merely, the mean maximum yield under non-adaptive stocking is declining with increasing stochasticity, while it remains more or less unchanged under adaptive stocking. Thereby, at a higher degree of stochasticity it is more beneficial for the improvement of a non-adaptive grazing rule to change to adaptive stocking than to adaptive rotation.

Our findings are supported by other modelling studies that, however, act on an annual time scale (Weber *et al.*, 2000; Stafford Smith and Foran, 1992; Riechers *et al.*, 1989). They also found that in a stochastic environment an adaptive stocking rule produce higher returns compared to a fixed stocking rule. Further, Weber *et al.* (2000) pointed out that adaptive stocking reduces the risk of range degradation under spatially heterogeneous grazing.

In contrast, other studies (Higgins *et al.*, 2007; Campbell *et al.*, 2000; Illius *et al.*, 1998) argue that an adaptive stocking rule is not beneficial compared to a conservative one. In our study, however, an adaptive rule produces a higher mean income from livestock sales than a constant stocking rule under stochastic conditions and a similar yield as under constant conditions. This difference might be caused by several reasons: the incorporation of competition between grass and woody vegetation in the aforementioned studies, the different livestock dynamics (i.e. population growth and trading rules), the occurrence of bush fire, or the disregard of the spatial component of rangelands management. A stepwise investigation of the different processes should be subject of further research to find out which conditions favour an adaptive and which a constant stocking rule. In this regard, it is also likely that not every kind of adaptation in the stocking rule causes an improvement. If stocking rules adapt to inappropriate system properties, this can lead to reduced performance. Our approach of adaptive stocking appears to be beneficial, probably because it directly adapts to the dry season's biomass, which is the critical resource for livestock survival (Illius and O'Connor, 1999).

Our results for both non-adaptive and adaptive stocking can be interpreted as reflection of the basic principle of maximum sustainable yield well-known from resource economics (Clark, 1976). This principle has originally been derived using a simple mathematical model. There is a likewise simple analysis for grazing systems by Noy-Meir (1975) showing that there is a certain optimum stocking density that sustainably maximizes the yield of the grazing system. Our results indicate that the principle of maximum sustainable yield is robust against the addition of complexity as in the case of the recent study. However, especially under variable precipitation it is difficult to estimate this value accurately. Hence, grazing management has a trade-off between maximising yield and minimizing the risk of degradation.

Therefore, we agree with Higgins *et al.* (2007) that livestock farmers should stock more conservative under stochastic than under deterministic climate condition, if they apply a constant stocking rule. The farmer is exposed to a higher risk of rangeland degradation, because the forage availability is fluctuating with variable precipitation. Therefore, the optimal stock size above that the rangeland collapses is less predictable with increasing stochasticity. In this case, a conservative low stocking rate would be the best strategy for risk avoidance and additionally, render the effort of constantly monitoring the rangeland unnecessary. However, the opportunity cost of such a constant low stocking rule increases with increasing rainfall variability and with more conservative stocking rates (Stafford Smith, 1996; Behnke and Kerven, 1994; Sandford, 1982).

Comparable to our results a long-term field study conducted by O'Reagain *et al.* (2009) found that a high constant stock size is not sustainable and can only be maintained in dry years with additional drought feeding, whereas under constant stocking near the carrying capacity animals coped very well though dry years. Moreover, they showed that adaptive stocking rules were sustainable, but performed not as good as light constant stocking. With reference to our results, we suppose that the adjusted stocking rates were estimated too high and laid beyond the optimal stocking rate.

However, owing to the huge variety of determinants, this study only analyses a limited range of possible management strategies. Further research should investigate the effect of different rules to define the standing time on a paddock. In this study, the standing time is only determined indirectly by rotation rule and stock density. The current rule, of complete grazing of the entire aboveground biomass, might have strong impact on the results, as it leads to a strong damage of range condition especially in the rainy season. Here are also different levels of adaptivity possible, ranging from a fixed constant standing time (cf. chapter 4) to a permanently consideration of a rotation event. These different methods to define the standing time should be evaluated regarding their importance in comparison to different stocking (Batabyal *et al.*, 2001) and rotation rules. Another interesting debate deals with the question of the suitability of rotational grazing systems in general (Briske *et al.*, 2008; Barnes *et al.*, 2008). In this regard, the comparison of our current results with a continuous grazing system that did not allow for any spatial adaptivity would be eligible. Furthermore, we apply a rather simple trading rule that creates high income fluctuation in the adaptive stocking rule under stochastic conditions. Therefore, it requires appropriate financial management, where large returns in years with many livestock sales are stored as savings to bridge low income years. Additionally, our model does not account for discounting and any fluctuation in the market price of livestock (e.g. depending on rainfall variability). However, this affects the economic evaluation of management strategies (Börner *et al.*, 2007) and has to be taken into account for the design of rangeland policies.

This study is carried out for a single typical vegetation type of semi-arid rangelands represented by one specific set of parameters. It provides important insights to the rangeland responds to different management strategies. However, rangelands under different conditions are characterised by functionally different dominant species and beyond that different community compositions (e.g. Anderson and Hoffman, 2007; Todd and Hoffman, 1999; Cowling *et al.*, 1994). To investigate the generality of the results, the analyses must be extended to other functional types. This can also shed light on the question if different types of vegetation favour a different management (see chapter 3.3). In this regard, we already established a basis with the pattern-oriented parameterisation approach we proposed in chapter 3.

The purpose of this study was to conduct a detailed analysis of different rotational grazing strategies that are ignored by most previous modelling studies (e.g. Teague *et al.*, 2009; Ash and Stafford Smith, 1996). Therefore, our modelling framework combines a spatially explicit farm structure with intra-annual time steps. This enables a detailed analysis of the spatio-temporal rangeland dynamics in response to different rotation rules. We gained a deeper understanding of underlying principles that lead to the observed pattern on the landscape scale. Moreover, this new insights can be incorporated with well-established discussions on rangeland management, like on the benefit of adaptive stocking rules (Campbell *et al.*, 2006; Sandford and Scoones, 2006).

Altogether, this study confirms that the consideration of several important system properties, like seasons of the year and spatial heterogeneity of available resources, are crucial components for appropriate rangeland management (Laca, 2009; Vetter, 2005). Moreover, we conclude that adaptivity is a powerful instrument for management improvement and risk mitigation if all important system properties are considered in the management approach.

Chapter 6

Synthesis and outlook

This doctoral thesis investigated management strategies for sustainable livestock grazing in semi-arid rangelands. In this chapter we summarise the main results regarding the research questions asked in chapter 1. Our approach posed both methodical challenges and applied concerns on different levels of semi-arid grazing systems. Altogether, we entered into the question: How to adapt semi-arid grazing systems to spatio-temporal heterogeneities in rangeland conditions, variable and changing climate conditions, and different individual needs and goals of livestock farmers? Particularly, we highlighted combined effects between and relative importance of different management components especially in consideration of spatial and temporal processes. The main goal of this study was the evaluation of management strategies under specific circumstances and the identification of strategies that are robust to a broad range of situations including different aspects of global change. Thus, this thesis contributes to a unified theory of adaptive grazing management that is still missing so far.

Therefore, in this study we developed a model framework (section 6.1.1) that allows the investigation of the relevant system components and introduced a method to parameterise such generic models (section 6.1.2). Using this integrated modelling approach, we analysed different management strategies (section 6.2.1) with a specific focus on climate conditions (section 6.2.2), vegetation characteristics (section 6.2.3), and economic objectives (section 6.2.4).

6.1 Methodical progress and achievements

6.1.1 Model framework

The research approach taken in this thesis posed the challenge to incorporate processes, relations, and feedbacks in semi-arid grazing systems on appropriate scales. The analysis aimed at general insights and broad understanding of rangeland management on an aggregated level, but equally it had to consider details of spatial and temporal system dynamic adequately. In this regard the integrated ecological-economic modelling framework developed in chapter 2 is appropriate to analyse questions on different system levels and at the same time to understand the functioning of grazing management strategies. Particularly, the chosen spatial and temporal resolution assists a proper analysis of basic principles of rotational grazing strategies on the farm level. Weekly time steps sufficiently enable the representation of intra-annual processes in vegetation dynamics as well as the implementation of rotational management strategies (chapters 3 – 5). Also, a spatial resolution of cells that represent single parts of a fenced pasture is adequate to represent local vegetation dynamics without incorporating too much detail (chapters 4 – 5). Furthermore, the spatially explicit representation of the rangeland allows the formation of a characteristic spatially heterogeneous pattern of vegetation condition that is particularly observed on large paddocks (Barnes *et al.*, 2008; Hart *et al.*, 1993).

Another benefit of the model structure is the description of vegetation dynamics by different processes that are physiologically interpretable. This explicit description allows to link different model parameter combinations to specific functional vegetation types and in turn a hands-on interpretation of the model results (chapter 3.3).

Also, the modular structure of the rangeland model enables a flexible use. Depending on a particular question, we can draw attention to single model components and at the same time ensure comparability of different model results. Likewise, simplifications of the model by disabling certain features are easily possible (e.g. excluding spatial interactions and intra-annual management in chapter 3.3). Overall, our modelling framework combines a spatially explicit farm structure with intra-annual time steps. Thus, the framework renders a detailed analysis of different rotational grazing strategies possible that was ignored by most previous modelling studies (Teague *et al.*, 2009; Ash and Stafford Smith, 1996).

6.1.2 Parameterisation of generic models

In order to derive general insights to semi-arid grazing systems from the generic model we needed to know what parameter values actually produce semi-arid rangeland dynamics. Only the knowledge of this range of plausible parameter values allows a general system analysis. For this purpose, in chapter 3 we developed and applied a novel pattern-oriented parameterisation method for generic models. This method uses qualitative patterns of general system behaviour to extract a broad range of biologically realistic parameter sets. This approach proved to be useful to strike a balance between analysing only one default parameter set, which probably loses a large quantity of possible system response, or the whole parameter space, which is likely to include implausible parameter ranges. Overall, the developed approach can be seen as extension of the strategy of pattern-oriented modelling (Grimm *et al.*, 2005) that was so far exclusively used in the context of specific case studies using mainly specific quantitative patterns (e.g. Rossmanith *et al.*, 2007; Wiegand *et al.*, 2004a).

In a first step, an investigation of the filtered parameter sets already generates a better understanding of the modelled system and moreover, the functioning of the model (chapter 3.2.2). In further steps, the filtered parameter space facilitates general system analysis for specific management questions (e.g. chapter 3.3). These analyses help to identify important processes that give hints, which vegetation type should be managed in which way. To this end, an extraction of only plausible parameter sets is essential to prevent misinterpretations that might have been caused by a consideration of the whole parameter space (Fig. 3.10).

6.2 Risk management in semi-arid grazing systems

The taken modelling approach did not target directly on optimisation of grazing management. Instead, it explored a broad range of possible system behaviour in relation to different arrangements of management strategies and system components. Thus, this approach aimed at a general system understanding that can help to create simple rules-of-thumb to classify different situations and to derive "what-if" scenarios that are often more appropriate for decision support than optimisation approaches (Stafford Smith, 1996).

6.2.1 Management strategies for semi-arid grazing systems

In order to investigate the impact of different management strategies on ecological rangeland condition, we analysed how different management components function, how they are interrelated, and to which system properties they should be adapted to improve grazing management. In different parts of this thesis we investigated three main principles of grazing management (Walker, 1995), namely stocking, temporal, as well as spatial distribution of livestock. In summary, all components have an influence on the result of grazing management and none is negligible in the first place. However, their relative importance and the generated type of system response differ. In the following, we will first describe the relative importance of single management components. Afterwards, we systematically reveal combined effects between different management components and demonstrate which adaptation is suitable to improve management.

Relative importance of single management components In agreement with other studies (e.g. Batabyal *et al.*, 2001; Holechek *et al.*, 1999b; Walker, 1995; O'Reagain and Turner, 1992) stocking management appeared to have the greatest influence on the performance of a strategy. Regardless of other management components the stocking rule has the highest potential to determine whether the rangeland is overused or utilised sustainably. In the systems considered, adaptive stocking has been found always beneficial compared to constant stocking if a strategy aims to sustain ecological conditions on the long run while maximising the livestock number (chapter 3.3 & 5). Another perspective taken in chapter 4 revealed that to some extent the stocking rate can increase the mean income with the consequence of increasing temporal income variability. However, too high stocking rates are always unfavourable and result in lower and more uncertain yields. In this regard, constant stocking is more vulnerable to overstocking than adaptive stocking (chapter 5), because it can not adjust the grazing pressure to prevent rangeland degradation.

Rotation rules that effect timing and spatial distribution of grazing also have an impact on the management performance and are a valuable tool for managing spatial heterogeneity in rangeland conditions. Each rotation rule results in a characteristic spatio-temporal pattern of rangeland conditions (chapter 5). The rules differ in the heterogeneity of this pattern (Fig. 5.2 & 5.4) and the maximum achievable income. Generally, the most effective spatial management is produced by a distinct cycle of heavy utilisation and long resting of a paddock, because it enables the full recovery of damaged paddocks up to a comparably high stock size. The strength of impact of the rotation rule, however, depends strongly on the applied stocking rule. Moreover, standing time enables to manipulate the local intensity of range utilisation. The duration a paddock is grazed has a strong impact on both amount and fluctuation of income (chapter 4). However, there is no universally optimal standing time and the adequate value must always be defined specifically for a certain situation.

The comparison of different arrangements in the farm structure that influence the spatial distribution of livestock shows that a higher subdivision of the farm results in an improvement of the management performance in terms of both increasing income and decreasing income fluctuations (chapter 4). This improvement is achieved by a more homogeneous spatial distribution of grazing in small paddocks (Barnes *et al.*, 2008). However, as the number of paddocks increases, pasture yield increases at a decreasing rate.

Interrelation between management components and role of adaptivity Over a broad range of situations the stocking rule is more important than the rotation rule to manipulate the mean income (chapter 5). Only around optimal livestock numbers the type of adaptation in the rotation rule has an influence on the general performance of the grazing strategy at all. For an adaptation in the rotation rule it turned out that seasonality is a pivotal system property, mainly because the vulnerability of vegetation to defoliation differs at certain phases of the year (Heady and Child, 1994). On the other hand, the decision to which vegetation component a strategy should be adapted has only a minor impact on aggregated system properties (i.e. mean herd size, mean livestock sales, and mean range condition on the whole farm), but has a great effect on the spatio-temporal pattern of vegetation condition (Fig. 5.2 & 5.4). On this lower aggregation level stocking rate and rotation rule are interrelated over the whole range of livestock numbers and the number of livestock determines directly which specific spatio-temporal vegetation pattern evolves from each rotation rule. This clarifies the importance of taking different scales into account to derive general understanding. However, adaptivity leads not always to an improved performance: incorrectly adapted rotation rules, which for example neglect seasonality, performs even worse than non-adaptive rotation. This accentuates the need for adapting carefully to all relevant system properties.

Also, number of paddocks, standing time, and stocking rate are tightly interrelated (chapter 4). Setting one of these three factors to a particular value requires specific values in the other factors to achieve a desired result. In this regard the number of paddocks shows a different system response than stocking rate and standing time (Fig. 4.2). An increasing number of paddocks always improve the performance of the management, while stocking rate and standing time are characterised by a unimodal relation. Here, the performance increases for increasing values until a certain optimum and decreases afterwards (Fig. 4.3 and Figs. 5.1 & 5.5). Again, a change in one factor requires changes in the other factors to obtain a favoured outcome.

6.2.2 Effect of climate conditions

Climate change is expected to have a huge impact on rangeland dynamics in semi-arid regions (Hoffman and Vogel, 2008). Therefore, we investigated different precipitation scenarios, including impact of uncertain as well as stable precipitation, and robustness of management strategies under different scenarios of climate change. Within the analysed ranges a change in climate conditions results in a shift in the system response, but does not change general relationships between the system components (chapter 4−5). Also, the ranking in suitability of different management strategies is mostly maintained. Chapter 4 shows that strategies that are most suitable to maintain sufficient income under decreasing precipitation and/or increasing rainfall variability are characterised again by many small paddocks, an adequately short standing time per paddock, and an adequately lower stocking rate. These most robust strategies also average the balance between large income and low coefficient of variation.

The results of chapter 5 revealed that an increasing uncertainty leads to an increasing advantage of adaptive versus constant stocking, while it barely impacts the difference between rotation rules. Nevertheless, properly adapted rotation rules are always favourable, even if they play a miner role in the adaptation to changing temporal climate variability. Overall increasing uncertainty requires higher caution in management to avoid high income losses and rangeland degradation. Following our results this can be obtained either by a low, conservative stocking rule or by an adaptive one that adapts to the available aboveground biomass. Adaptive stocking requires a higher management effort than conservative stocking. However, this will be worthwhile in regions with high rainfall variability where conservative stocking rates have to be low and therefore, opportunity costs are high (Stafford Smith, 1996).

A large change in climate conditions might also lead to a shift in dominant vegetation types (Briske *et al.*, 2003; Fynn and O'Connor, 2000). This could change the performance of management strategies which appeared to be suitable under the present conditions.

6.2.3 Importance of vegetation characteristics

In chapter 3.2.2 we characterised different vegetation types that plausibly describe semi-arid vegetation dynamics. It is an important management issue how these vegetation types differ in their response to different grazing strategies. Chapter 3.3 reveals that the impact of adaptive stocking rules ranges from moderate improvement to extremely strong benefit compared to constant stocking. Thereby, it turned out that particularly those types benefit from adaptive stocking whose storage condition is characterised by strong intra-annual dynamics and therefore, respond strongly to external drivers (i.e. fluctuating rainfall and grazing). Hence, the higher the vulnerability of vegetation types to external drivers is, the larger is the importance to carefully adapt the management. This confirms that vegetation characteristics are important variables to be considered in management planning as for different types a certain change in the management strategy improves the result significantly, while it hardly matters for others.

Nevertheless, the variety of vegetation types was neglected in chapters 4 – 5 and we chose one specific parameter set. This allowed a detailed analysis of fundamental spatio-temporal processes and patterns in grazing management. We learned also how the system response can be observed and analysed on different scales. On this basis a further investigation of all types can now provide a general picture of possible management response in semi-arid grazing systems.

6.2.4 Socio-economic perspectives

The suitability of a management strategy always depends on the farmer's individual management goals (Savory and Butterfield, 1998; Connor, 1991). Therefore, we analysed different kinds of economic evaluation of grazing strategies to estimate how different objectives affect the range of suitable management options. Our results reveal that under all considered objectives generally a high complexity and proper adaptivity of the management strategy is beneficial and increases the maximum possible herd size while still ensuring ecological sustainability (chapter 3.3 – 5).

In particular in chapter 4 we evaluated several management strategies from two different perspectives. The first perspective was to consider a mean-CV preference in the income. Here, we observed that an increasing number of paddocks improve both mean income and CV of income. Furthermore, we found that standing time and stocking rate can be used to adjust the management outcome to the desired balance between mean income and CV. For the second perspective we considered a farmer who aims at gaining a certain minimum income in most years (safety-first criterion). In this case we identified a whole set of suitable strategies that shrinks with increasing income requirements. Generally, this identification of the range of possible strategies that satisfy minimum income requirements under various conditions is particularly valuable in systems where people have to deal with unexpected changes and a high uncertainty. Our analysis facilitates the finding of robust strategies that are suitable for a broad range of situations. We detected, for example, strategies as most suitable for the considered range of requirements that average the trade-off between mean income and CV of income. Overall, different objectives are often not mutually exclusive and can be linked to facilitate decision support (Fig. 4.6).

Changes in external drivers like climate conditions require flexibility in the farmer's management approach. We confirmed that not all strategies which suite a certain objective under current climate conditions will suffice under other climate regimes that are characterised by decreased and/or more variable rainfall. However, a strategy that satisfies high economic requirements also appears to be a good strategy to manage climate change.

In all studies the management strategies were evaluated only by economic indicators, including herd size and number of sold livestock. Nevertheless, at the same time we observed also the ecological condition of the rangeland (i.e. storage biomass). Thereby, we found that strategies which create suitable economic conditions for a long time period of 100 years are also beneficial to maintain the rangeland in rather good conditions.

6.2.5 Conclusions for the relevance of rotational grazing

The presented results reveal that there are several general principles which characterise grazing strategies that secure a certain income and/or support income maximisation under various situations: namely a large number of paddocks, well-adapted stocking and rotation rules as well as an appropriate definition of stocking rate and standing time. These settings result in beneficial management strategies, mainly because they are characterised by a proper ratio between grazing and resting of paddocks. This provides sufficient time for recovery of previously used paddocks without overutilising the currently grazed paddock.

Rotational grazing is particularly designed to organise explicitly grazing and resting on commercial livestock farms. In this regard, our studies confirm that rotational grazing is a valuable tool that has the ability to shape the spatio-temporal pattern of rangeland condition and hence, a high potential to improve grazing management (chapter 5). Chapter 4 shows that most rotational grazing strategies perform better in risk management than continuous grazing, and largely are more robust to scenarios of climate change and increasing economic demands.

These benefits are found, even though the full complexity of environmental conditions, including heterogeneities in spatial and intra-annually precipitation, soil types and topography, as well as livestock related processes, including selective grazing, trampling, and parasite infections, were neglected in our study. We hypothesise that a consideration of each of these components in the model would emphasise the importance of rotational grazing to improve rangeland utilisation. However, we also assume that due to this additional complexity of real systems the grazing management should be even more carefully adapted to the multitude of different factors than our results for the simplified system suggest. In those complex ecosystems the risk of management failure due to inadequate adaptation is high. Therefore, a high degree of knowledge, skills, effort, and money for management as well as monitoring is needed to apply rotational grazing properly (Budd and Thorpe, 2009; Beukes *et al.*, 2002).

Literature reviews of Briske *et al.* (2008) and O'Reagain and Turner (1992) found no evidence for a general advantage of rotational grazing schemes compared to continuous grazing and argued that the advocacy of rotational grazing is mostly founded on perceptions and anecdotal interpretations. We agree that rotational grazing might not be an adequate solution for every situation and depends on environmental as well as economic circumstances and personal objectives. However, it is also possible that some field studies might not have applied a properly adapted management strategy and would have benefited from other forms of rotation management. Indeed, it is difficult to choose the best management strategy in advance. Here, models can foster the development of adequate grazing plans for specific situations. Moreover, the vegetation types filtered in chapter 3.2.2 can help to characterise vegetation traits for which rotational grazing would be beneficial compared to continuous grazing and when it would give no advantage or even be harmful. Nevertheless, even if it is possible to recommend improved management strategies, they might not be adopted by land managers for several reasons (see Gillespie *et al.*, 2007). In order to encourage adoption Gillespie *et al.* (2007) suggested increased educational effort in combination with economic incentives for adoption.

Finally, we conclude that in several situations rotational grazing can be beneficial to improve the performance of grazing management. Therefore, the farmer must fulfil different qualifications, including management skills and financial opportunities. Also, it must be deliberated carefully whether it pays off to run such kind of complex grazing system or if a simpler management approach actually suites the farmer's needs better.

6.3 Outlook and future research

This research derived valuable insights and understanding of relations between important components of semi-arid grazing systems. However, an analysis of the entire range of all possible combinations of system and management components was beyond the scope of this thesis. Further investigation of specific questions using the same model framework will contribute piecewise to a big picture. Furthermore, the modelling cycle needs to be "closed" (Schmolke *et al.*, 2010; Rykiel, 1996): the results should be validated and discussed with rangeland scientists and stakeholders to assess the model results and see how the praxis could profit from this approach.

6.3.1 Spatio-temporal heterogeneities on larger scales and their potential for adaptation

In this thesis we characterised suitable management strategies that act on the local scale of a livestock farm. The suitability of these strategies might change in the context of global change. For example, increasing economic requirements in combination with ongoing land degradation and expected consequences of climate change might exceed the capability of the local management strategies taken into account in this study. Particularly, further increasing fluctuations and decreasing values of primary production due to changes in precipitation regimes or overgrazing might create limitations for management on a local scale. A promising approach to buffer scarce and uncertain local resources availability is the incorporation of different spatial scales into a management strategy. Therefore, further research needs to characterise management strategies that allow also a large scale spatio-temporal diversification of grazing. Such diversifications can be useful to provide access to the heterogeneity of landscapes that is particularly important in extensively grazed ecosystems (Hobbs *et al.*, 2008).

In this regard, it is an important question, how to adapt management strategies to take advantage of environmental heterogeneities across different spatial and temporal scales. For this purpose, the model has to incorporate a spatially heterogeneous distribution of environmental condition and vegetation types as well as spatio-temporal heterogeneously fluctuating precipitation (Augustine, 2010; Swemmer *et al.*, 2007). To this end, already existing tools can be linked to the model framework, for example to represent spatio-temporal correlations in rainfall dynamics (e.g. Eisinger and Wiegand, 2008).

In order to adapt to environmental heterogeneities, management strategies could diversify the grazed locations on a regional scale. One possible option is multiple farm ownership in different geographical regions. We hypothesise that the ownership of another farm enables to buffer rainfall variability, especially if the distance between these farms is large. This spatial diversification spreads the risk of dramatic income losses, e.g. as consequence of local droughts. Another option to buffer local fluctuations can be temporary renting of farmland. Here, a farmer utilises a part of another farm for a certain period of time to maintain a higher stock size in drought years than the own farmland would support. This transfer of livestock to rented pastures allows taking advantage of potentially higher rainfall or better vegetation conditions on other farms. It can also be an option to provide rest (for storage recovery) to several paddocks on the own farm without destocking of the herd. A further more radical approach would be to restore large scale mobility in commercial rangelands (Vetter, 2005). This, however, would require a fundamental change in mindsets (Niamir-Fuller, 1999) and sophisticated management regulations as it requires large areas under commune tenure that ensure access to key resources. In addition, also more local options, like an increase of the farm size, have to be investigated. First of all, this increase would probably lead to an increase of the livestock capacity on the farm. Moreover, it would also increase the capacity to rest paddocks and to create forage buffers for bad rainfall years. Nevertheless, it is not obvious if the increase of the farm size has just a scaling effect or if and how other components, including environmental heterogeneities and minimum requirements of a farmer, affect the management result.

All suggested strategies could be beneficial to adapt rangeland management in the context of global change. However, they might also be costly and involve unintentional side effects. They also require an initial financial investment and have to cope with institutions regulating private properties and regional access regimes. The modelling framework developed in this thesis can be used to investigate under which circumstances such strategies are feasible and how they have to be arranged to ensure long term sustainability.

6.3.2 Contribution of remote sensing to semi-arid rangeland modelling

Our study investigated general principles of rangeland management. We emphasised particularly spatio-temporal dynamics of vegetation conditions and focused on different plausible virtual vegetation types. However, the model framework can also be used for "real-world" applications. In this regard, remote sensing is a promising tool to provide data of vegetation characteristics over large areas in semi-arid regions (Asner, 2004). For example, it can foster a rangeland analysis in a specific region and the assessment of local vegetation conditions can be used for model parameterisation and validation (Roughgarden *et al.*, 1991). Also, a broad analysis of time-series of different satellite images can facilitate the identification of different vegetation types to review the findings of chapter 3.

Moreover, remote sensing is a valuable tool to detect the impacts of grazing on managed rangelands (Hill, 2004). An important threat for rangeland management that is promoted and often mediated by grazing activities is woody encroachment (Asner *et al.*, 2004). This increasing amount of undesired woody plants imbalance the grass to bush ratio and in turn decreases the carrying capacity of livestock on the rangeland. In order to differentiate between grass and woody biomass and quantify their land cover satellite images can be analysed. In this regard, we made already the first steps and tested differed classification techniques to assess the degree of woody encroachment on commercial livestock farms (Schröter *et al.*, 2011). As result of that study we highlighted especially the need of ground truth data to facilitate further research. This would render a specific investigation of the problem of woody encroachment in semi-arid rangelands possible. The combination of satellite and field information with an adjusted version of our rangeland model (chapter 2) that incorporates the woody vegetation component (c.f. Scheiter and Higgins, 2007) can increase the understanding of the encroaching process.

Overall, connecting remote sensing with ecological modelling is a promising approach (Pickup, 1996; Hanson *et al.*, 1992). Linking static spatial data with dynamic process models allows to understand the functioning of ecosystem processes. In this case, such an approach can reveal why different management strategies cause problems like woody encroachment and which strategies are suitable to prevent undesired system shifts and ensure a sustainable management.

Bibliography

Abel, N. O. J. and Blaikie, P. M. (1989). Land degradation, stocking rates and conservation policies in the communal rangelands of Botswana and Zimbabwe. *Land Degradation and Rehabilitation*, **1**, 101–123.

Acocks, A. P. H. (1966). Non-selective grazing as a means of veld reclamation. *Proceedings Grassland Society of South Africa*, **1**, 33–39.

Adger, W. N.; Arnell, N. W. and Tompkins, E. L. (2005). Successful adaptation to climate change across scales. *Global Environmental Change*, **15**(2), 77–86.

Adler, P.; Raff, D. and Lauenroth, W. (2001). The effect of grazing on the spatial heterogeneity of vegetation. *Oecologia*, **128**, 465–479.

Anderies, J. M.; Janssen, M. A. and Walker, B. H. (2002). Grazing management, resilience, and the dynamics of a fire-driven rangeland system. *Ecosystems*, **5**, 23–44.

Anderson, P. and Hoffman, M. (2007). The impacts of sustained heavy grazing on plant diversity and composition in lowland and upland habitats across the Kamiesberg mountain range in the Succulent Karoo, South Africa. *Journal of Arid Environments*, **70**(4), 686–700.

Andrew, M. H. (1988). Grazing impact in relation to livestock watering points. *Trends in Ecology & Evolution*, **3**(12), 336 – 339.

Archer, S. and Smeins, F. E. (1991). Ecosystem-level processes. In: *Grazing management: an ecological perspective.* (Heitschmidt, R. K. and Stuth, J. W., eds), pp. 109–140. Timber Press, Portland.

Ash, A. J. and Stafford Smith, D. M. (1996). Evaluating stocking rate impacts in rangelands: Animals don't practice what we preach. *Rangeland Journal*, **18**(2), 216–243.

Asner, G. P. (2004). Biophysical remote sensing signatures of arid ans semiarid ecosystems. In: *Remote Sensing for Natural Resource Management and Environmental Monitoring* (Ustin, S. L., ed.), pp. 53–109. John Wiley & Sons, New Jersey.

Asner, G. P.; Elmore, A. J.; Olander, L. P.; Martin, R. E. and Harris, A. T. (2004). Grazing systems, ecosystem responses, and global change. *Annual Review of Environment and Resources*, **29**, 261–299.

Augustine, D. J. (2010). Spatial versus temporal variation in precipitation in a semiarid ecosystem. *Landscape Ecology*, **25**, 913–925.

Barnes, M. K.; Norton, B. E.; Maeno, M. and Malechek, J. C. (2008). Paddock size and stocking density affect spatial heterogeneity of grazing. *Rangeland Ecology & Management*, **61**(4), 380–388.

Basset, A.; DeAngelis, D. L. and Diffendorfer, J. E. (1997). The effect of functional response on stability of a grazer population on a landscape. *Ecological Modelling*, **101**(2-3), 153–162.

Batabyal, A. A.; Biswas, B. and Godfrey, E. B. (2001). On the choice between the stocking rate and time in range management. *Environmental & Resource Economics*, **20**(3), 211–223.

Baumgärtner, S.; Becker, C.; Frank, K.; Müller, B. and Quaas, M. (2008). Relating the philosophy and practice of ecological economics: The role of concepts, models, and case studies in inter- and transdisciplinary sustainability research. *Ecological Economics*, **67**(3), 384–393.

Baumgärtner, S. and Quaas, M. F. (2009). Ecological-economic viability as a criterion of strong sustainability under uncertainty. *Ecological Economics*, **68**(7), 2008–2020.

Beaumont, P. (1993). *Drylands: Environmental management and development*. Routledge, London and New York.

Behnke, R. and Kerven, C. (1994). Redesigning for risk: tracking and buffering environmental variability in Africa's rangelands. *ODI Natural Research Perspectives*, **No.1**, 1–8.

Behnke, R. H.; Scoones, I. and Kerven, C. (1993). *Range Ecology at Disequilibrium, new models of natural variability and pastoral adaptation in African savannas*. ODI, London.

Beukes, P. C.; Cowling, R. M. and Higgins, S. I. (2002). An ecological economic simulation model of a non-selective grazing system in the Nama Karoo, South Africa. *Ecological Economics*, **42**(1-2), 221–242.

Briske, D. D.; Derner, J. D.; Brown, J. R.; Fublendor, S. D.; Teague, W. R.; Havstad, K. M.; Gillen, R. L.; Ash, A. J. and Willms, W. D. (2008). Rotational grazing on rangelands: Reconciliation of perception and experimental evidence. *Rangeland Ecology & Management*, **61**(1), 3–17.

Briske, D. D.; Fuhlendorf, S. D. and Smeins, F. E. (2003). Vegetation dynamics on rangelands: a critique of the current paradigms. *Journal of Applied Ecology*, **40**(4), 601–614.

Börner, J.; Higgins, S. I.; Kantelhardt, J. and Scheiter, S. (2007). Rainfall or price variability: What determines rangeland management decisions? A simulation-optimization approach to South African savannas. *Agricultural Economics*, **37**(2-3), 189–200.

Brown, J. and Kothmann, M. (2009). Rotational grazing and the profession and practice of rangeland management. *Rangelands*, **31**(5), 3–4.

Bruinsma, J. (2003). *World Agriculture: Towards 2015/2030, An FAO Perspective.* Earthscan and FAO, London and Rome.

Budd, B. and Thorpe, J. (2009). Benefits of managed grazing: A manager's perspetive. *Rangelands*, **31**(5), 11–14.

Campbell, B. M.; Dore, D.; Luckert, M.; Mukamuri, B. and Gambiza, J. (2000). Economic comparisons of livestock production in communal grazing lands in Zimbabwe. *Ecological Economics*, **33**(3), 413–438.

Campbell, B. M.; Gordon, I. J.; Luckert, M. K.; Petheram, L. and Vetter, S. (2006). In search of optimal stocking regimes in semi-arid grazing lands: One size does not fit all. *Ecological Economics*, **60**(1), 75 – 85.

Carpenter, S. R.; Mooney, H. A.; Agard, J.; Capistrano, D.; DeFries, R. S.; Díaz, S.; Dietz, T.; Duraiappah, A. K.; Oteng-Yeboah, A.; Pereira, H. M.; Perrings, C.; Reid, W. V.; Sarukhan, J.; Scholes, R. J. and Whyte, A. (2009). Science for managing ecosystem services: Beyond the millennium ecosystem assessment. *Proceedings of the National Academy of Sciences*, **106**(5), 1305–1312.

Clark, C. W. (1976). *Mathematical Bioeconomics: The Optimal Management of Renewable Resources.* Wiley, New York, 1990, 2$^{\text{nd}}$ Edition.

Connor, J. R. (1991). Social and ecological influences on grazing management. In: *Grazing management: an ecological perspective.* (Heitschmidt, R. K. and Stuth, J. W., eds), pp. 191–200. Timber Press, Portland.

Conway, G. R. (1977). Mathematical models in applied ecology. *Nature*, **269**(5626), 291–297.

Coughenour, M. B. (1991). Spatial components of plant-herbivore interactions in pastoral, ranching, and native ungulate ecosystems. *Journal of Range Management*, **44**(6), 530–542.

Cowling, R. M.; Esler, K. J.; Midgley, G. F. and Honig, M. A. (1994). Plant functional diversity, species diversity and climate in arid and semi-arid southern Africa. *Journal of Arid Environments*, **27**(2), 141–158.

Díaz, S.; Briske, D. D. and McIntyre, S. (2002). Range management and plant functional types. In: *Global rangelands: progress and prospects* (Grice, A. C. and Hodgkinson, K. C., eds), pp. 81–100. CAB International, Wallingford, UK.

Dean, W. R. J. and Macdonald, I. A. W. (1994). Historical changes in stocking rates of domestic livestock as a measure of semi-arid and arid rangeland degradation in the Cape Province, South Africa. *Journal of Arid Environments*, **26**(3), 281–298.

Delgado, C.; Rosegrant, M.; Steinfeld, H.; Ehui, S. and Courbois, C. (1999). Livestock to 2020 - the next food revolution. *Food, Agriculture and Environment Discussion Paper*, **28**, 72 pp. Rome, Italy: IFPRI, FAO and ILRI.

Dregne, H. E. (2002). Land degradation in the drylands. *Arid Land Research and Management*, **16**(2), 99–132.

Easterling, D. R.; Meehl, G. A.; Parmesan, C.; Changnon, S. A.; Karl, T. R. and Mearns, L. O. (2000). Climate extremes: Observations, modeling, and impacts. *Science*, **289**(5487), 2068–2074.

Eisinger, D. and Wiegand, K. (2008). SERGE: a spatially explicit generator of local rainfall in southern Africa. *South African Journal of Science*, **104**, 37–42.

Ellis, J. E. and Swift, D. M. (1988). Stability of african pastoral ecosystems: Alternate paradigms and implications for development. *Journal of Range Management*, **41**(6), 450–459.

FAO (2009). *The state of food and agriculture - Livestock in the balance.* FAO, Rome.

Frank, K.; Baumgärtner, S.; Becker, C.; Müller, B. and Quaas, M. (2006). Ecological-economic models for sustainable grazing in semi-arid regions: between concepts and case studies. In: *The Changing Culture and Nature of Namibia: Case Studies* (Leser, H., ed.). Publishing House Basler Afrika Bibliographien, Basel – Windhoek.

Fuhlendorf, S. D.; Briske, D. D. and Smeins, F. E. (2001). Herbaceous vegetation change in variable rangeland environments: The relative contribution of grazing and climatic variability. *Applied Vegetation Science*, **4**(2), 177–188.

Fynn, R. W. S. and O'Connor, T. G. (2000). Effect of stocking rate and rainfall on rangeland dynamics and cattle performance in a semi-arid savanna, south africa. *Journal of Applied Ecology*, **37**(3), 491–507.

Gillespie, J.; Kim, S.-A. and Paudel, K. (2007). Why don't producers adopt best management practices? An analysis of the beef cattle industry. *Agricultural Economics*, **36**(1), 89–102.

Grimm, V. (1994). Mathematical models and understanding in ecology. *Ecological Modelling*, **75-76**, 641 – 651. State-of-the-Art in Ecological Modelling proceedings of ISEM's 8th International Conference.

Grimm, V.; Berger, U.; Bastiansen, F.; Eliassen, S.; Ginot, V.; Giske, J.; Goss-Custard, J.; Grand, T.; Heinz, S. K.; Huse, G.; Huth, A.; Jepsen, J. U.; Jorgensen, C.; Mooij, W. M.; Müller, B.; Pe'er, G.; Piou, C.; Railsback, S. F.; Robbins, A. M.; Robbins, M. M.; Rossmanith, E.; Rüger, N.; Strand, E.; Souissi, S.; Stillman, R. A.; Vabo, R.; Visser, U. and DeAngelis, D. L. (2006). A standard protocol for describing individual-based and agent-based models. *Ecological Modelling*, **198**(1-2), 115–126.

Grimm, V.; Berger, U.; DeAngelis, D. L.; Polhill, G.; Giske, J. and Railsback, S. F. (2010). The ODD protocol: a review and first update. *Ecological Modelling*, **221**, 2760–2768.

Grimm, V.; Frank, K.; Jeltsch, F.; Brandl, R.; Uchmanski, J. and Wissel, C. (1996). Pattern-oriented modelling in population ecology. *Science of the Total Environment*, **183**(1-2), 151–166.

Grimm, V.; Revilla, E.; Berger, U.; Jeltsch, F.; Mooij, W. M.; Railsback, S. F.; Thulke, H. H.; Weiner, J.; Wiegand, T. and DeAngelis, D. L. (2005). Pattern-oriented modeling of agent-based complex systems: Lessons from ecology. *Science*, **310**(5750), 987–991.

Hanson, J. D.; Anderson, G. L. and Haas, R. H. (1992). Combining remote sensing techniques with simulation modelling for assessing rangeland resources. *Geocarto International*, **7**(1), 99–104.

Hart, R. H.; Bisso, J.; Samuel, M. J. and Waggoner, J. W. (1993). Grazing systems, pasture size, and cattle grazing behavior, distribution and gains. *Journal of Range Management*, **46**(1), 81–87.

Heady, H. F. (1999). Perspectives on rangeland ecology and management. *Rangelands*, **21**, 23–33.

Heady, H. F. and Child, D. R. (1994). *Rangeland Ecology and Management*. Westview Press, Boulder, San Francisco, Oxford.

Heitschmidt, R. and Walker, J. (1983). Short duration grazing and the Savory grazing method in perspective. *Rangelands*, **5**(4), 147–150.

Heitschmidt, R. K. and Taylor, Jr., C. A. (1991). Livestock production. In: *Grazing management: an ecological perspective.* (Heitschmidt, R. K. and Stuth, J. W., eds), pp. 161–177. Timber Press, Portland.

Helldén, U. (1991). Desertification: Time for an assessment? *Ambio*, **20**(8), 372–383.

Higgins, S. I.; Kantelhardt, J.; Scheiter, S. and Börner, J. (2007). Sustainable management of extensively managed savanna rangelands. *Ecological Economics*, **62**(1), 102–114.

Hill, M. J. (2004). Grazing agriculture: Managed pastures, grassland, and rangeland. In: *Remote Sensing for Natural Resource Management and Environmental Monitoring* (Ustin, S. L., ed.), pp. 449–530. John Wiley & Sons, New Jersey.

Hobbs, N. T.; Galvin, K. A.; Stokes, C. J.; Lackett, J. M.; Ash, A. J.; Boone, R. B.; Reid, R. S. and Thornton, P. K. (2008). Fragmentation of rangelands: Implications for humans, animals, and landscapes. *Global Environmental Change*, **18**(4), 776–785.

Hodgson, J. and Da Silva, S. C. (2000). Sustainability of grazing systems: Goals, concepts and methods. In: *Grassland Ecophysiology and Grazing Ecology* (Lemaire, G.; Hodgson, J.; de Moraes, A.; Nabinger, C. and de F. Carvalho, P. C., eds), pp. 209–231. CAB International, Wallingford.

Hoekstra, T. W. and Joyce, L. A. (1999). Management of arid and semi-arid ecological systems. In: *Arid Lands Management: Toward Ecological Sustainability* (Hoekstra, T. W. and Shachak, M., eds). University of Illinois Press.

Hoffman, M. T. and Vogel, C. (2008). Climate change impacts on African rangelands. *Rangelands*, **30**, 12–17.

Holechek, J. L. (1983). Considerations concerning grazing systems. *Rangelands*, **5**(5), 208–211.

Holechek, J. L. (1988). An approach for setting the stocking rate. *Rangelands*, **10**(1), 10–14.

Holechek, J. L.; Gomez, H.; Molinar, F. and Galt, D. (1999a). Grazing studies: What we've learned. *Rangelands*, **21**(2), 12–16.

Holechek, J. L.; Pieper, R. D. and Herbel, C. H. (1998). *Range Management.* Upper Saddle River, NJ, USA: Prentice Hall., 3^{ed} Edition.

Holechek, J. L.; Thomas, M.; Molinar, F. and Galt, D. (1999b). Stocking desert rangelands: What we've learned. *Rangelands*, **21**(6), 8–12.

Holling, C. S. (1966). The strategy of building models of complex ecological systems. In: *Systems Analysis in Ecology* (Watt, K. E. F., ed.), pp. 195–214. Academic Press, New York.

Hormay, A. L. (1970). Principles of rest-rotation grazing and multiple use land management. Technical report, USDA-FS, Training Text 4.

Hudak, A. T. (1999). Rangeland mismanagement in South Africa: Failure to apply ecological knowledge. *Human Ecology*, **27**(1), 55–76.

Huntley, B. J. and Walker, B. H. (1982). *Ecology of Tropical Savannas*. Springer, Berlin, Heidelberg, New York.

Ibanez, J.; Martinez, J. and Schnabel, S. (2007). Desertification due to overgrazing in a dynamic commercial livestock-grass-soil system. *Ecological Modelling*, **205**(3-4), 277–288.

Illius, A. W.; Derry, J. F. and Gordon, I. J. (1998). Evaluation of strategies for tracking climatic variation in semi-arid grazing systems. *Agricultural Systems*, **57**(3), 381–398.

Illius, A. W. and O'Connor, T. G. (1999). On the relevance of nonequilibrium concepts to arid and semiarid grazing systems. *Ecological Applications*, **9**(3), 798–813.

Illius, A. W. and O'Connor, T. G. (2000). Resource heterogeneity and ungulate population dynamics. *Oikos*, **89**, 283–294.

IPCC (2007). Climate change 2007: Synthesis report. contribution of working groupsI, II and III to the fourth assessment report of the intergovernmental panel on climate change. [Core Writing Team, Pachauri, R.K and Reisinger, A., eds.] 2007, 104 pp. Technical report, IPCC, Geneva, Switzerland.

IPCC (2008). Climate change and water. Technical Paper VI of the Intergovernmental Panel on Climate Change, [Bates, B., Kundzewicz, Z.W., Wu, S., and Palutikof, J.P., eds.]. 210 pp.

Janssen, M. A.; Anderies, J. M. and Walker, B. H. (2004). Robust strategies for managing rangelands with multiple stable attractors. *Journal of Environmental Economics and Management*, **47**, 140–162.

Jeltsch, F.; Milton, S. J.; Dean, W. R. J. and Van Rooyen, N. (1997). Simulated pattern formation around artificial waterholes in the semi-arid Kalahari. *Journal of Vegetation Science*, **8**(2), 177–188.

Jeltsch, F.; Stephan, T.; Wiegand, T. and Weber, G. E. (2001). Arid rangeland management supported by dynamic spatially-explicit simulation models. In:

Sustainable Land-Use in Deserts (Breckle, S.; Veste, M. and Wucherer, W., eds), pp. 229–240. Springer, Berlin.

Knapp; K., A.; Beier, C.; Briske, D. D.; Classen, A. T.; Luo, Y.; Reichstein, M.; Smith, M. D.; Smith, S. D.; Bell, J. E.; Fay, P. A.; Heisler, J. L.; Leavitt, S. W.; Sherry, R.; Smith, B. and Weng, E. (2008). Consequences of more extreme precipitation regimes for terrestrial ecosystems. *BioScience*, **58**, 811–821.

Kothmann, M. (2009). Grazing methods: A viewpoint. *Rangelands*, **31**(5), 5–10.

Kramer-Schadt, S.; Revilla, E.; Wiegand, T. and Breitenmoser, U. (2004). Fragmented landscapes, road mortality and patch connectivity: modelling influences on the dispersal of Eurasian lynx. *Journal of Applied Ecology*, **41**(4), 711–723.

Kramer-Schadt, S.; Revilla, E.; Wiegand, T. and Grimm, V. (2007). Patterns for parameters in simulation models. *Ecological Modelling*, **204**(3–4), 553–556.

Laca, E. A. (2000). Modelling spatial aspects of plant-animal interactions. In: *Grassland Ecophysiology and Grazing Ecology* (Lemaire, G.; Hodgson, J.; de Moraes, A.; Nabinger, C. and de F. Carvalho, P. C., eds), pp. 209–231. CAB International, Wallingford.

Laca, E. A. (2009). New approaches and tools for grazing management. *Rangeland Ecology & Management*, **62**(5), 407–417.

Lauenroth, W. K. and Sala, O. E. (1992). Long-term forage production of North American shortgrass steppe. *Ecological Applications*, **2**(4), 397–403.

Le Houérou, H. N. (1996). Climate change, drought and desertification. *Journal of Arid Environments*, **34**(2), 133–185.

Le Houérou, H. N.; Bingham, R. L. and Skerbek, W. (1988). Relationship between the variability of primary production and the variability of annual precipitation in world arid lands. *Journal of Arid Environments*, **15**, 1–18.

Liu, J.; Dietz, T.; Carpenter, S. R.; Alberti, M.; Folke, C.; Moran, E.; Pell, A. N.; Deadman, P.; Kratz, T.; Lubchenco, J.; Ostrom, E.; Ouyang, Z.; Provencher, W.; Redman, C. L.; Schneider, S. H. and Taylor, W. W. (2007). Complexity of coupled human and natural systems. *Science*, **317**(5844), 1513–1516.

May, R. M. (1976). Simple mathematical models with very complicated dynamics. *Nature*, **261**(5560), 459–467.

McAllister, R. R. J.; Smith, D. M. S.; Stokes, C. J. and Walsh, F. J. (2009). Patterns of accessing variable resources across time and space: Desert plants, animals and people. *Journal of Arid Environments*, **73**(3), 338–346.

McKay, M. D.; Conover, W. J. and Beckman, R. J. (1979). A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. *Technometrics*, **221**, 239–245.

Merrill, L. B. (1954). A variation of deferred rotation grazing for use under southwest range conditions. *Journal of Range Management*, **7**(4), 152–154.

Millennium Ecosystem Assessment (2005a). *Ecosystems and Human Well-Being: Current State & Trends*. Island Press, Washington DC.

Millennium Ecosystem Assessment (2005b). *Ecosystems and Human Well-Being: Desertification Synthesis*. Island Press, Washington DC.

Müller, B. (2006). *Sustainable grazing management in semi-arid rangelands. An ecological-economic modelling approach.* PhD Dissertation, UFZ - Centre for Environmental Research Leipzig-Halle.

Müller, B.; Frank, K. and Wissel, C. (2007). Relevance of rest periods in non-equilibrium rangeland systems - a modelling analysis. *Agricultural Systems*, **92**(1-3), 295–317.

Niamir-Fuller, M. (1999). *Managing Mobility in African Rangelands: The Legitimization of Transhumance*. Intermediate Technology Publications, London.

Noy-Meir, I. (1975). Stability of grazing systems - application of predator-prey graphs. *Journal of Ecology*, **63**(2), 459–481.

Noy-Meir, I. (1978). Grazing and production in seasonal pastures: Analysis of a simple model. *Journal of Applied Ecology*, **15**(3), 809–835.

Noy-Meir, I. (1981). Spatial effects in modelling of arid ecosystems. In: *Arid Land Ecosystems* (Goodall, D. W. and Perry, R. A., eds), pp. 411–432. Cambridge University Press, Cambridge.

Noy-Meir, I. (1982). Stability of plant-herbivore models and possible applications to savanna. In: *Ecology and tropical savannas* (Huntley, B. and Walker, B., eds), pp. 591–609. Springer, Berlin.

O'Connor, T. G.; Haines, L. M. and Snyman, H. A. (2001). Influence of precipitation and species composition on phytomass of a semi-arid African grassland. *Journal of Ecology*, **89**(5), 850–860.

Oesterheld, M.; Loreti, J.; Semmartin, M. and Sala, O. E. (2001). Inter-annual variation in primary production of a semi-arid grassland related to previous-year production. *Journal of Vegetation Science*, **12**(1), 137–142.

Olbrich, R.; Quaas, M. F. and Baumgärtner, S. (2009). Sustainable use of ecosystem services under multiple risks - a survey of commercial cattle farmers in semi-arid rangelands in Namibia. *University of Lüneburg Working Paper Series in Economics*, **Working Paper No. 137**, 1–24.

O'Reagain, P. J. and Turner, J. R. (1992). An evaluation of the empirical basis for grazing management recommendations for rangeland in southern Africa. *Journal of the Grassland Society of Southern Africa*, **9**, 38–49.

O'Reagain, P. O.; Bushell, J.; Holloway, C. and Reid, A. (2009). Managing for rainfall variability: effect of grazing strategy on cattle production in a dry tropical savanna. *Animal Production Science*, **49**(2), 85–99.

Owen-Smith, N. (1990). Demography of a large herbivore, the greater kudu Tragelaphus strepsiceros, in relation to rainfall. *Journal of Animal Ecology*, **59**(3), 893–913.

Paruelo, J. M.; Oesterheld, M.; Di Bella, C. M.; Arzadum, M.; Lafontaine, J.; Cahuepé, M. and Rebella, C. M. (2000). Estimation of primary production of subhumid rangelands from remote sensing data. *Applied Vegetation Science*, **3**(2), 189–195.

Perrings, C. (1994). Stress, shock and the sustainability of resource use in semiarid environments. *The Annals of Regional Science*, **28**, 31–53.

Perrings, C. (1997). Stress, shock and the sustainability of resource unse in semiarid environments. In: *Economics of Ecological Resources* (Perrings, C., ed.). Edward Elgar, Cheltenham, UK.

Pickup, G. (1994). Modeling patterns of defoliation by grazing animals in rangelands. *Journal of Applied Ecology*, **31**(2), 231–246.

Pickup, G. (1996). Estimating the effects of land degradation and rainfall variation on productivity inrangelands: An approach using remote sensing and models of grazing and herbage dynamics. *Journal of Applied Ecology*, **33**(4), 819–832.

Popp, A.; Domptail, S.; Blaum, N. and Jeltsch, F. (2009). Landuse experience does qualify for adaptation to climate change. *Ecological Modelling*, **220**(5), 694 – 702.

Pringle, H. J. R. and Landsberg, J. (2004). Predicting the distribution of livestock grazing pressure in rangelands. *Austral Ecology*, **29**, 31–39.

Pütz, S. (2006). *Long-Term Impact of Grazing on Vegetation under Stochastic Climate: A Cross-Scale Simulation Study.* UFZ-Dissertation 07/2006, University of Potsdam.

Quaas, M. F.; Baumgartner, S.; Becker, C.; Frank, K. and Müller, B. (2007). Uncertainty and sustainability in the management of rangelands. *Ecological Economics*, **62**(2), 251–266.

Reid, R. S.; Galvin, K. A. and Kruska, R. L. (2007). The global significance of extensive grazing lands and pastoral societies: An introduction. In: *Fragmentation of semi-arid and arid landscapes: Consequences for human and natural systems.* (Galvin, K. A.; Reid, R. S.; Behnke, R. H. and Hobbs, N. T., eds), pp. 1–24. Springer, Dordrecht.

Reynolds, J. F.; Stafford Smith, D. M.; Lambin, E. F.; Turner, B. L.; Mortimore, M.; Batterbury, S. P. J.; Downing, T. E.; Dowlatabadi, H.; Fernandez, R. J.; Herrick, J. E.; Huber-Sannwald, E.; Jiang, H.; Leemans, R.; Lynam, T.; Maestre, F. T.; Ayarza, M. and Walker, B. (2007). Global desertification: Building a science for dryland development. *Science*, **316**(5826), 847–851.

Riechers, R. K.; Conner, J. R. and Heitschmidt, R. K. (1989). Economic consequences of alternative stocking rate adjustment tactics - a simulation approach. *Journal of Range Management*, **42**(2), 165–171.

Rossmanith, E.; Blaum, N.; Grimm, V. and Jeltsch, F. (2007). Pattern-oriented modelling for estimating unknown pre-breeding survival rates: The case of the lesser spotted woodpecker (Picoides minor). *Biological Conservation*, **135**(4), 555–564.

Roughgarden, J.; Running, S. W. and Matson, P. A. (1991). What does remote sensing do for ecology? *Ecology*, **72**(6), 1918–1922.

Roy, A. D. (1952). Safety first and the holding of assets. *Econometrica*, **20**(3), 431–450.

Rykiel, E. J. (1996). Testing ecological models: the meaning of validation. *Ecological Modelling*, **90**(3), 229–244.

Saltelli, A.; Chan, K. and (eds.), E. M. S. (2000). *Sensitivity Analysis.* Wiley, Chichester, West Sussex, England.

Sandford, S. (1982). Pastoral strategies and desertification: Opportunism and conservation in dry lands. In: *Desertification and Development: Dryland Ecology in Social Perspective* (Spooner, B. and Mann, H. S., eds). Academic Press.

Sandford, S. and Scoones, I. (2006). Opportunistic and conservative pastoral strategies: Some economic arguments. *Ecological Economics*, **58**(1), 1 – 16.

Savory, A. and Butterfield, J. (1998). *Holistic Management: A New Framework for Decision Making.* Island Press, Washington, D.C.

Savory, A. and Parsons, S. D. (1980). The Savory grazing method. *Rangelands*, **2**(6), 234–237.

Scheiter, S. and Higgins, S. I. (2007). Partitioning of root and shoot competition and the stability of savannas. *American Naturalist*, **170**, 587–601.

Schlesinger, W. H.; Reynolds, J. F.; Cunningham, G. L.; Huenneke, L. F.; Jarrell, W. M.; Virginia, R. A. and Whitford, W. G. (1990). Biological feedbacks in global desertification. *Science*, **247**(4946), 1043–1048.

Schmolke, A.; Thorbek, P.; DeAngelis, D. L. and Grimm, V. (2010). Ecological models supporting environmental decision making: a strategy for the future. *Trends in Ecology & Evolution*, **25**(8), 479–486.

Schröter, M.; Jakoby, O.; Olbrich, R.; Eichhorn, M. and Baumgärtner, S. (2011). Remote sensing of bush encroachment on commercial cattle farms in semi-arid rangelands in Namibia. In: *Environmental Modeling for Sustainable Regional Development: System Approaches and Advanced Methods* (Olej, V.; Obrsálová, I. and Krupka, J., eds), pp. 327–343. IGI Global, Hershey.

Schwarz, R. (2004). Sustaining productive ecosystems in face of risk. *GeoJournal*, **59**, 219–225.

Schwinning, S. and Parsons, A. J. (1999). The stability of grazing systems revisited: spatial models and the role of heterogeneity. *Functional Ecology*, **13**(6), 737–747.

Scoones, I. (1994). New directions for pastoral development in africa. In: *Living with uncertainty: New directions for pastoral development in Africa* (Scoones, I., ed.), pp. 1–36. International Institute for Environment and Development, London.

Skarpe, C. (1991). Impact of grazing in savanna ecosystems. *Ambio*, **20**(8), 351–356.

Skarpe, C. (1992). Dynamics of savanna ecosystems. *Journal of Vegetation Science*, **3**(3), 293–300.

Smit, B. and Pilifosova, O. (2001). Adaptation to climate change in the context of sustainable development and equity. In: *Climate Change 2001: Impacts, Adaptation and Vulnerability* (McCarthy, J. J.; Canziani, O. F.; Leary, N. A.; Dokken, D. J. and White, K. S., eds), pp. 877–911. Cambridge University Press, Cambridge, New York, Oakleigh, Madrid, Cape Town.

Smithers, J. and Smit, B. (1997). Human adaptation to climatic variability and change. *Global Environmental Change*, **7**(2), 129–146.

Snyman, H. A. and Fouché, H. J. (1993). Estimating seasonal herbage production of a semi-arid grassland based on veld condition, rainfall, and evapotranspiration. *African Journal of Range & Forage Science*, **10**(1), 21–24.

Stafford Smith, D. M. (1996). Management of rangelands: paradigms at their limits. In: *The Ecology and Management of Grazing Systems* (Hodgson, J. and Illius, A. W., eds), pp. 325–357. CAB International, Wallingford.

Stafford Smith, D. M. and Foran, B. (1992). An approach to assessing the economic risk of different drought management tactics on a South Australian pastoral sheep station. *Agricultural Systems*, **39**(1), 83–105.

Stein, M. (1987). Large sample properties of simulations using latin hypercube sampling. *Technometrics*, **29**, 143–151.

Stephan, T.; Jeltsch, F.; Wiegand, T. and Breiting, H. A. (1998). Sustainable farming at the edge of the Namib: analysis of land use strategies by a computer simulation model. In: *Ecosystems and Sustainable Development* (Uso, J. L.; Brebbia, C. A. and Power, H., eds), pp. 41–50. Computational Mechanics Publication, Southampton.

Stoddart, L. A. (1975). Plant morphology and physiology in relation to range management. In: *Range Management*, pp. 104–145. McGraw-Hill College.

Stuth, J. and Maraschin, G. E. (2000). Sustainable management of pasture and rangelands. In: *Grassland Ecophysiology and Grazing Ecology* (Lemaire, G.; Hodgson, J.; de Moraes, A.; Nabinger, C. and de F. Carvalho, P. C., eds), pp. 339–354. CAB International, Wallingford.

Stuth, J. W. (1991). Foraging behaviour. In: *Grazing management: an ecological perspective.* (Heitschmidt, R. K. and Stuth, J. W., eds), pp. 201–223. Timber Press.

Sullivan, S. and Rhode, R. (2002). On non-equilibrium in arid and semi-arid grazing systems. *Journal of Biogeography*, **29**, 1595–1618.

Swemmer, A. M.; Knapp, A. K. and Snyman, H. A. (2007). Intra-seasonal precipitation patterns and above-ground productivity in three perennial grasslands. *Journal of Ecology*, **95**(4), 780–788.

Tainton, N. M. (1999). *Veld Management in South Africa.* University of Natal Press, Pietermaritzburg.

Teague, W. R.; Kreuter, U. P.; Grant, W. E.; Diaz-Solis, H. and Kothmann, M. M. (2009). Economic implications of maintaining rangeland ecosystem health in a semi-arid savanna. *Ecological Economics*, **68**(5), 1417–1429.

Telser, L. G. (1955). Safety first and hedging. *The Review of Economic Studies*, **23**(1), 1–16.

Tietjen, B. and Jeltsch, F. (2007). Semi-arid grazing systems and climate change: a survey of present modelling potential and future needs. *Journal of Applied Ecology*, **44**(2), 425–434.

Todd, S. W. and Hoffman, M. T. (1999). A fence-line contrast reveals effects of heavy grazing on plant diversity and community composition in Namaqualand, South Africa. *Plant Ecology*, **142**, 169–178.

Trlica, M. J. (2006). Grass growth and response to grazing. Natural Resources Series, Range. No. 6.108.

UNEP (1997). *World Atlas of Desertification.* Arnold, London, 2nd Edition.

van Keulen, H. and Breman, H. (1990). Agricultural development in the West African Sahelian region: a cure against land hunger? *Agriculture, Ecosystems & Environment*, **32**(3-4), 177–197.

van Noordwijk, M. (2002). Scaling trade-offs between crop productivity, carbon stocks and biodiversity in shifting cultivation landscape mosaics: the FALLOW model. *Ecological Modelling*, **149**(1-2), 113–126.

Vetter, S. (2005). Rangelands at equilibrium and non-equilibrium: recent developments in the debate. *Journal of Arid Environments*, **62**(2), 321–341.

Walker, B. and Abel, N. (2002). Resilient rangelands: adaptation in complex systems. In: *Panarchy: Understanding Transformations in Human and Natural Systems* (Gunderson, L. and Holling, C., eds). Island Press, Washington, D.C.

Walker, B.; Holling, C. S.; Carpenter, S. R. and Kinzig, A. P. (2004). Resilience, adaptability and transformability in social-ecological systems. *Ecology and Society*, **9**(2), URL: http://www.ecologyandsociety.org/vol9/iss2/art5/.

Walker, B. H. (2002). Ecological resilience in grazed rangelands: a generic case study. In: *Resilience and the behavior of large-scale systems* (Gunderson, L. and Pritchard, L., eds), pp. 183–194. Island Press, Washington, DC.

Walker, B. H.; Ludwig, D.; Holling, C. S. and Peterman, R. M. (1981). Stability of semi-arid savanna grazing systems. *Journal of Ecology*, **69**(2), pp. 473–498.

Walker, J. W. (1993). Rangeland ecology - understanding and managing change. *Ambio*, **22**(2–3), 80–87.

Walker, J. W. (1995). Viewpoint - grazing management and research now and in the next millennium. *Journal of Range Management*, **48**(4), 350–357.

Walter, H. and Volk, O. H. (1954). *Grundlagen der Weidewirtschaft in Südwestafrika*. Eugen Ulmer, Stuttgart.

Ward, D.; Saltz, D. and Ngairorue, B. T. (2004). Spatio-temporal rainfall variation and stock management in arid Namibia. *Journal of Range Management*, **57**(2), 130–140.

Weber, G. E.; Jeltsch, F.; Van Rooyen, N. and Milton, S. J. (1998). Simulated long-term vegetation response to grazing heterogeneity in semi-arid rangelands. *Journal of Applied Ecology*, **35**(5), 687–699.

Weber, G. E.; Moloney, K. and Jeltsch, F. (2000). Simulated long-term vegetation response to alternative stocking strategies in savanna rangelands. *Plant Ecology*, **150**(1–2), 77–96.

Weltz, M. A.; Dunn, G.; Reeder, J. and Frasier, G. (2003). Ecological sustainability of rangelands. *Arid Land Research and Management*, **17**(4), 1532–4982.

Wessels, K. J.; Prince, S. D.; Carroll, M. and Malherbe, J. (2007). Relevance of rangeland degradation in semiarid northeastern South Africa to the nonequilibrium theory. *Ecological Applications*, **17**(3), 815–827.

Westoby, M.; Walker, B. and Meir, I. N. (1989). Opportunistic management for rangelands not at equilibrium. *Journal of Range Management*, **42**(4), 266–274.

Wiegand, T.; Jeltsch, F.; Hanski, I. and Grimm, V. (2003). Using pattern-oriented modeling for revealing hidden information: a key for reconciling ecological theory and application. *Oikos*, **100**(2), 209–222.

Wiegand, T.; Knauer, F.; Kaczensky, P. and Naves, J. (2004a). Expansion of brown bears (Ursus arctos) into the eastern Alps: a spatially explicit population model. *Biodiversity and Conservation*, **13**, 79–114.

Wiegand, T.; Revilla, E. and Knauer, F. (2004b). Dealing with uncertainty in spatially explicit population models. *Biodiversity and Conservation*, **13**, 53–78.

Wiegand, T.; Snyman, H. A.; Kellner, K. and Paruelo, J. M. (2004c). Do grasslands have a memory: Modeling phytomass production of a semiarid south african grassland. *Ecosystems*, **7**, 243–258.

Wiegand, T.; Wiegand, K. and Pütz, S. (2008). Grazing models. In: *Encyclopedia of Ecology* (Jørgensen, S. E. and Fath, B. D., eds), pp. 1773–1782. Elsevier, Amsterdam.

Wissel, C.; Jeltsch, F.; Stephan, T. and Wiegand, T. (1996). Analyse und Entwicklung nachhaltiger Bewirtschaftungsstrategien mit Hilfe von Simulationsmodellen: Trockengebiete im südlichen Afrika. In: *Welternährung und*

Landwirtschaft: Zukunftsfähige Entwicklungen (Anonymous, ed.), pp. 91–104. Deutsche Welthungerhilfe, Bonn.

Wolfson, M. M. and Tainton, N. M. (1999). The morphology and physiology of the major forage plants. In: *Veld Management in South Africa* (Tainton, N. M., ed.), pp. 54–79. University of Natal Press, Pietermaritzburg.

Woodward, S. J. R. (1998). Dynamical systems models and their application to optimising grazing management. In: *Agricultural Systems Modelling and Simulations* (Peart, M. R. and Curry, R. B., eds), pp. 419–473. Marcal Dekker Inc., New York.

WRI (2000). *World Resources 2000-2001 People and Ecosystems: The Fraying Web of Life*. World Resources Institute, Washington, D.C.

Acknowledgements

An dieser Stelle möchte all jenen danken, die mich während der Promotionszeit sowie auf meinem bisherigen wissenschaftlichen Lebensweg unterstützt und somit diese Arbeit ermöglicht haben!

Mein ganz besonderer Dank gilt meinen Betreuern Karin Frank und Martin Quaas. Karin Frank hat diese Arbeit mit viel Enthusiasmus und wissenschaftlichem Ideenreichtum betreut und durch viele intensive sowie richtungsweisende Diskussionen entscheidend zum Entstehen der Arbeit beigetragen. Vor allem danke ich ihr aber für ihre uneingeschränkte Unterstützung bei allen kleinen und größeren Herausforderungen während der letzten Jahre. Ebenso gilt mein Dank Martin Quaas, der mir die Arbeit an diesem Projekt anvertraute, mir viele Freiheiten ließ und die Arbeit durch gute Ideen und seine analytische Sichtweise bereicherte. Außerdem danke ich Uta Berger herzlich für die Übernahme des Zweitgutachtens.

Besonders danken möchte ich Volker Grimm, der mich vor nunmehr fast zehn Jahren für die ökologische Modellierung begeisterte, mich seitdem in vielen Höhen und Tiefen des Modelliererdaseins unterstützte und wenn nötig mit einer weiteren "Geschichte am Rande" neu motivierte.

Mein Dank geht auch an Thomas Banitz, Florian Hartig, Mira Kattwinkel, Birgit Müller und Franziska Taubert, die Teile dieser Arbeit kommentierten und dadurch zu ihrer Verbesserung beitrugen. Mira danke ich besonders dafür, dass sie so ziemlich jeden Paragraphen dieser Arbeit mit Rotstift bearbeitete und mich ansonsten immer sehr motivierte.

Allen aktuellen und ehemaligen Mitgliedern der ÖSA (Department Ökologische Systemanalyse am UFZ) möchte ich besonders herzlich für die tolle, produktive und entspannte Arbeitsatmosphäre danken, die ich in den letzten Jahren genießen durfte. Vor allem danke ich meinen Bürokollegen und Freunden Claudi und Flo, für ihre Gesellschaft und das Teilen der alltäglichen Freuden und Frustrationen. Thomas, Tami, Finn, Mathias, Kama, Birgit, Alex, Guy, Jürgen, Jula, Sandro, Michael, Romina, Hanna, Jeroen, Franzi und vielen anderen gilt mein Dank für die bereichernden wissenschaftlichen sowie "unwissenschaftlichen" Diskussionen und Gespräche und die schöne Zeit bei unzähligen Tassen Kaffee und vielen anderen Gelegenheiten. Bei Michael und allen anderen Beteiligten möchte ich mich für den gemeinsamen Spaß bei der Organisation von zahlreichen Winterschulen bedanken. Marcus danke ich für seine tatkräftige Unterstützung bei der Praktikantenbetreuung sowie Hilfestellungen bei jeglichen Problemen mit GIS. Ebenso sei Gabi, Andreas und Heike für ihre technische und administrative Unterstützung gedankt.

Außerdem danke ich dem Helmholtz-Zentrum für Umweltforschung – UFZ sowie der Helmholtz Interdisciplinary Graduate School for Environmental Research (HIGRADE) die mir hervorragende Arbeitsmöglichkeiten boten und eine vielfältige wissenschaftliche Weiterbildung ermöglichten. Ebenso möchte ich meinen Kollegen aus dem “SUESUn”-Projekt für die gute Zusammenarbeit und dem Bundesministerium für Bildung und Forschung (BMBF) für die finanzielle Unterstützung dieser Promotion danken (grant No. 01UN0607).

Des Weiteren gilt mein Dank den Farmern und Wissenschaftlern aus Namibia, die uns auf unseren Forschungsreisen teils interessiert, teils mit Skepsis an ihrem Wissen über semi-aride Weidesysteme teilhaben ließen.

Meinen Freunden und besonders meinen Mitbewohnern “unterm Dach” verdanke ich die nötige Ablenkung und eine schöne Zeit jenseits der Doktorarbeit die mit Sicherheit entscheidend zum Entstehen dieser Arbeit beitrugen. Besonders möchte ich mich bei meinen Eltern bedanken, für ihre stetige Unterstützung und ihr Vertrauen.