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Sustainable grazing management in semi-arid rangelands
An ecological-economic modelling approach

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Sustainable grazing management in semi-arid rangelands

An ecological-economic modelling approach

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Abstract

The loss of utilisable rangeland in semi-arid areas, often termed as "desertification", results in enormous economic and social costs worldwide. Only adaptive management strategies are able to cope with these systems, which are largely driven by unpredictable and stochastic rainfall. Since grazing in semi-arid regions is characterized by strong feedback mechanisms between economic and ecological factors, global changes, such as new opportunities of economic risk management, affect the rangeland system as a whole.

This study aims to contribute to the identification of basic principles for sustainable grazing management. It tackles the challenge of selecting suitable ecological and economic risk management strategies to cope with risky income without worsening the state of the pasture. The approach emphasizes learning from existing management systems through the use of ecological-economic modelling. Two apparently successful management systems in Namibia are used as a starting point for a broader analysis: the Gamis Karakul sheep farm and the land use system of the semi-nomadic Ova-Himba. Although these economic systems differ strongly (commercial rest-rotation farming versus opportunistic subsistence farming), their management seems to have similarities: the importance of pasture resting and of adapting livestock numbers to available forage.

This PhD thesis contributes substantial insights about the relevance and functioning of pasture resting for sustainable grazing management in semi-arid regions. Assessment of the two case studies leads to the hypothesis that resting in the rainy season, particularly during wet years, is fundamental for ensuring pasture productivity under low regeneration potential of the vegetation.

Additionally, the thesis highlights that resting during wet years acts as a risk reducing strategy, specifically buffering income variability in the short term while ensuring high pasture productivity in the long term. The study reveals that access to economic risk management strategies, such as rain-index-insurance, may change farmer's behaviour. Therefore the preferences of the individual farmer, in particular his risk aversion and time horizon, are shown to be highly influential. These determine whether he will choose less conservative grazing strategies following access to insurance.

The used approach - learning from existing apparently successful grazing strategies by ecological-economic modelling - offers a powerful tool for tackling new questions related to global change. The scope and the limits for generalizing the key factors discovered for sustainable grazing management can be easily detected under changing ecological, climatic and economic conditions.

1 Introduction

1.1 Relevance

Arid or semi-arid areas cover one third of earth's land surface (UNCCD, 2004). They are characterised by low annual mean but extreme fluctuations in rainfall. Droughts are an intrinsic part of the system. The livelihood of at least one billion people depends on the use of this land. Livestock farming is the prevalent form of land use in these areas. In Africa for instance, livestock is bred on 85% of the land used for agriculture (UNEP, 2004). Grazing in semi-arid regions is characterized by strong feedback mechanisms between economic and ecological factors (Perrings & Walker, 1995; Beukes *et al.*, 2002). Economic yield is directly linked to livestock number and hence to pasture condition. On the other hand, ecological resources are easily damaged by inappropriate use. In the past people have dealt with harsh climatic conditions using age-old strategies including flexible response to climatic variations such as nomadic herding (Breman & De Wit, 1983; Niamir-Fuller, 2000). In recent decades these strategies have become less feasible due to changing economic and political circumstances, and due to internal drivers such as population growth.

Inappropriate strategies can cause desertification - the overwhelming problem in semi-arid areas (Schlesinger *et al.*, 1990). Desertification (or degradation) - the loss of productive land - is believed to be a consequence of a combination of climate variability and human mismanagement. It carries huge ecological, economic and social costs. Income losses worldwide of US$42 billion per year are estimated to result from the loss of productive land due to degradation (UNCCD, 2004). Therefore the crucial task for the future is to prevent the risk of degradation by identifying appropriate grazing management strategies.

In addition to this risk of long-term decline in pasture productivity, livestock farmers have to deal with the risk associated with high fluctuations in income from year to year caused by variable rainfall (Pickup & Stafford Smith, 1993; Wang & Hacker, 1997; Quaas *et al.*, 2004). In the past, people were forced to use means of self-insurance or self-protection to deal with this risk. Apart from income diversification, an example of self-protection is the granting of grazing reserves for times of drought.

In the past, governmental and international organisations have attempted to reduce the impact of prolonged droughts, for instance by offering supplementary feeding or increasing accessible rangeland through installation of boreholes. One explanation given for why these strategies have partly failed, is that the feedback mechanisms of such risk management strategies on a farmer's behaviour and hence on pasture conditions were not adequately taken into account (Breman & De Wit, 1983; Milton *et al.*, 2003).

Currently, an increasing number of risk management measures are offered by the market. Rain-index-insurance is one form, recently proposed for livestock farming: If the farmer has closed an insurance contract, a payout is granted by the insurance company should precipitation fall short of a prior specified threshold (Skees & Barnett, 1999; Miranda & Vedenov, 2001; Turvey, 2001). The consequences of the availability of such insurance on the chosen grazing management strategy have not previously been investigated.

1.2 Aims of the study and approach

To fill the gaps highlighted in the previous paragraph a comprehensive understanding of the dynamics and the crucial aspects in (semi-) arid regions is a prerequisite. This study aims to contribute to the identification of basic principles of sustainable grazing management strategies. Sustainability is understood in this study as maintenance of the long-term productivity of the vegetation whilst simultaneously providing sufficient income for the land user (cf. Pickup & Stafford Smith, 1993). The approach taken is to investigate and learn from existing management systems. With the help of ecological-economic modelling, this study intends to generate hypotheses for the basic principles of sustainable use and to test their applicability under different ecological and socio-economic conditions.

For that purpose, two apparently successful management systems in Namibia are investigated (Figure 1.1). The first example is the commercial Gamis Karakul sheep farm. The farmer applies a flexible strategy which combines short-term adaptation of the stocking rate to the available forage and long-term adaptation by resting one third of the paddocks in years with sufficient rainfall.

The second example are the semi-nomadic Ova-Himba in northern Namibia who have until very recently used a sophisticated management system involving season-dependent pasture use, preservation of reserves for times of drought and sanctions to prevent rule breaking.

Although these economic systems differ strongly (commercial rotational farming system versus opportunistic subsistence farming), the management seems to have similarities: the importance of pasture resting and the flexible adaptation of livestock numbers to available forage. For both, the question tackled is: What are

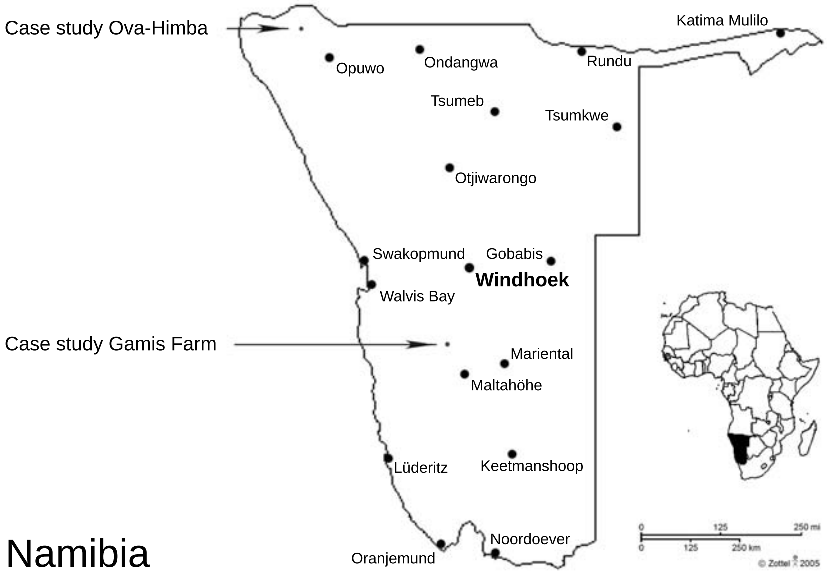

Figure 1.1: Location of the two case studies Karakul sheep Gamis Farm and semi-nomadic Ova-Himba in Namibia.

the crucial components of the management system that ensure sustainability? In response to this question two problems are addressed: (1) What happens if parts of the strategy are changed? (2) Would traditional strategies need to be altered under climate or other global changes (for example, as influenced by access to insurance or installation of infrastructure for the sale and purchase of livestock)?

As previously articulated, grazing in semi-arid regions is characterized by strong interactions between economic and ecological factors. Therefore one part of this study is dedicated to an explicit exploration of interacting ecological and economic dynamics. This focuses on the Gamis Farm example, investigating the role of access to risk management strategies, such as rain-index insurance, on the chosen grazing strategy. The hypothesis tested is whether, with access to market insurance, the ecological risk management strategy - resting in years with sufficient rainfall - is no longer applied (Baumgärtner, 2006, forthcoming). The consequence of this may be degradation of the pasture.

My methodical approach to answering these questions is through the use of modelling, valuable for improving the understanding of such systems in relation to specified questions (Wissel *et al.*, 1996; Jeltsch *et al.*, 2001). Such an approach is considered integral to fulfilling the study's key aim of detecting basic principles for sustainable land use. Furthermore, a modelling analysis enables the impact of alternative management options on ecological and economic target variables to be compared with ease (Perrings & Stern, 2000). In addition, simulation models are effective in detecting the consequences of land use in semi-arid regions, with impacts usually only visible following long time spans (Briske *et al.*, 2003). Data from field experiments that span these long time periods are seldom available.

Associated with alternative knowledge bases and purposes, two different simulation models, with different levels of detail, were constructed in this study. The model created to reflect the Gamis Farm case study was based on the knowledge gained by a previously built detailed spatially explicit ecological simulation model (Stephan *et al.*, 1998). For the purposes of this study, a highly abstract ecological-economic model was constructed, in which details unnecessary for the posed question were omitted. For the second case study, the ecological context and the management system used by the semi-nomadic Ova-Himba was modelled using a higher level of detail, supporting an assessment of the consequences of alternative management strategies on vegetation composition and the productivity of different pastures.

In constructing the two models no standard modelling software was applied. Instead, with the use of C++ programming language, the models could be tailored to the specific needs.

1.3 Structure of this thesis

The thesis is divided into three parts. The **first part** (Chapter 2) investigates the relevance of pasture resting as part of the management system in semi-arid rangelands. The focus is on two aspects: firstly on the ecological conditions under which resting is necessary and secondly on the appropriate time of resting (wet or dry years). In addressing these aspects, the management system of the Gamis Farm (Namibia) is assessed as a starting point. Thereafter, a broader range of strategies and ecological conditions is examined towards improving the understanding of the basic principles for sustainable range management. Following a review of previous research in relation to the role of resting in non-equilibrium rangelands, the study's ecological model is presented. The Gamis-Strategy, with resting granted in years with sufficient rainfall, is compared to strategies with resting in dry years and to pure restocking-destocking management practises without resting. The decisive mechanisms determining vegetation and livestock dynamics for the system are identified. The found results and their contributions to the current equilibrium vs. non-equilibrium debate are discussed (cf. Cowling, 2000; Sullivan & Rohde, 2002; Briske *et al.*, 2003; Vetter, 2005).

The **second part** (Chapter 3) also examines the Gamis Farm case study, explicitly investigating the interactions between ecological and economic factors. The role of one form of risk management strategies, rain-index insurance, on a farmer's decision, about what grazing strategy to employ, is investigated. The hypothesis tested is, whether access to rain-index-insurance leads to less conservative grazing strategies. The potential of rain-index insurances is reviewed, as well as the appropriateness of the safety-first rule as a decision criterion of the farmer. A safety-first criterion signifies that before a decision maker tends to maximize his expected income, he wants to reach a minimal income with a certain probability (Telser, 1955). The ecological model, used in part 1, is expanded into an ecological-economical model through the inclusion of relevant economic aspects such as the decision criterion and the functioning of the insurance. The influence of an individual farmer's preferences on his decision and subsequent impact on the environment are explored. The role of resting in rainy years as a management strategy to reduce risk is discussed.

The **third part** (Chapter 4) analyses the range management system of the semi-nomadic Ova-Himba people. Firstly the ecosystem, the management system and the changes in these are depicted. A land use system tailored ecological model, including impacts of grazing strategies on the vegetation composition and productivity on different pastures, is then presented. The dynamics of the traditional land use system in the long-term is investigated and compared to strategies where components of the traditional strategy are no longer carried out. Furthermore the consequences of altered socio-economic conditions, such as market access to livestock purchase, on the system are analysed. The discussion section emphasises the importance of the timing of resting for high productivity of the pasture and debates the contribution of indigenous knowledge to sustainable grazing management.

Each of the three parts represents a distinct theme and can be read as an autonomous unit. Three crucial issues - ecological, economic and methodical - are addressed by each of these parts. These are integrated in a synthesising discussion (Chapter 5: Synthesis). Firstly, the relevance of resting of a part of the pasture for the ecological condition of the farm and its functioning is pointed out. Secondly, the interplay of ecological and economic risk management strategies is discussed, considering exemplarily resting and rain-index-insurance. Thirdly, the study's approach, to derive general basic principles following an examination of existing, apparently successful management strategies through ecological-economic modelling, is evaluated.

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2 Relevance of rest periods in non-equilibrium rangeland systems - a modelling analysis[1]

> "A simple management principle is that the way in which rangeland is rested is usually more important than the way in which it is utilized"
>
> Snyman (1998, p.646)

2.1 Abstract

The worldwide loss of utilisable rangeland in (semi-) arid areas results in huge economic and social costs. Only adaptive management strategies are able to cope with these systems, which are mainly driven by unpredictable and stochastic rainfall. The aim of the study was to investigate the relevance of rest periods as part of the management scheme in these non-equilibrium rangeland systems. The starting point of the analysis is an approved management system - the Karakul sheep Gamis Farm (Namibia). The farmer applies a flexible strategy which combines short-term adaptation of the stocking rate to the available forage and long-term adaptation by resting a third of the paddocks in years with sufficient rainfall.

We developed a simulation model that focuses on the key dynamics of this non-equilibrium system. Beginning with the strategy used on the Gamis Farm, a set of alternative grazing strategies was defined, all adapted to the available forage but differing in whether and when resting is granted for a part of the pasture. The effectiveness of these strategies was compared according to the long-term productivity of the pasture and the farmer's livelihood.

Our results reveal ecological settings during which resting is essential for the recovery of the vegetation in a fluctuating environment, as well as those during which it is not. The growth rates of both the vegetation and of the livestock are demonstrated to be highly influential. Rests during wet years are crucial for the regeneration of the pasture. We conclude that even though a non-equilibrium

[1]A slightly modified version of this chapter is accepted for publication in *Agricultural Systems*: B. Müller, B., Frank, K., Wissel, C.: Relevance of rest periods in non-equilibrium rangeland systems - a modelling analysis.

rangeland system is assumed, the application of pure opportunistic strategies - destocking in times of drought and fast post-drought restocking - are not always adequate to maintain the long-term productivity of the pasture. Rest periods are indispensable when vegetation has a low regeneration potential. On an applied level, the study emphasises that improved farming conditions (supplementary feeding, unrestricted options to purchase livestock) may run the risk of ecological as well as economic damages.

2.2 Introduction

A third of earth's land surface consists of arid or semi-arid regions. The livelihoods of at least one billion people depend on the use of this land (UNCCD, 2004). Hence, the loss of utilisable rangeland carries huge economic and social costs. Adequate management strategies that maintain the long-term productivity of the pasture need to be identified. To do so, a fundamental understanding of the underlying dynamics of the ecosystem is required which includes taking into account the feedback-mechanisms between vegetation and livestock in a highly fluctuating environment.

Fifteen years ago, a paradigm shift took place with respect to herbivore-vegetation dynamics in (semi-) arid systems. Previously, it was argued that rangeland systems behave as equilibrium systems primarily influenced by biotic factors, with grazing being the main driver of vegetation change. Consequently, degradation (the loss of productive land) was attributed to excessive stocking rates (Lamprey, 1983; Dean & MacDonald, 1994). A relatively low fixed stocking rate was recommended as the appropriate management strategy in order to avoid overuse of the vegetation. In contrast to this, the so-called New Rangeland Science argues that these (semi-) arid systems, characterized by highly unpredictable and variable rainfall, behave as non-equilibrium systems. That means that abiotic factors such as prior rainfall are considered to be the main drivers of the system dynamics, and biotic factors such as grazing to be only of marginal influence (Behnke Jr *et al.*, 1993; Sandford, 1994; Scoones, 1994). It is argued that fixed stocking rates are unsuitable in a variable environment and instead "opportunistic strategies" (Westoby *et al.*, 1989) are favoured. These strategies are characterized by a close adaptation of the stocking rate to the available forage: At the first indication of a pending drought the animals are destocked and after the drought fast restocking is carried out. These restocking-destocking management strategies, provided they are adapted to the available forage, should be sufficient in maintaining the long-term productivity of the rangelands. By implication additional measures, like rest periods for a part of the pasture, are obsolete and inappropriate for the efficient use of the pasture. For a review and critique of the current paradigms, see Cowling (2000) and Briske *et al.* (2003).

The successful Gamis Farm in Namibia contradicts these recommended strategies. This commercial Karakul sheep farm closely adapts the number of sheep to the available forage. In addition, part of the pasture is temporarily rested. In the rangeland literature, the danger of degradation in years of drought is emphasized and full stocking (according to available forage) is promoted in wet years (Livingstone, 1991). However, running counter to this intuitive view of relieving the burden on vegetation during dry years, resting on the Gamis Farm is instead carried out in years with sufficient rainfall and not during dry years. In order to assess this strategy, in association with the specific soil, climatic and environmental conditions on this farm, a detailed simulation model was constructed by T. Stephan (Stephan *et al.*, 1996, 1998a,b), referred to hereafter as the Stephan-Model. This study found that alternative strategies, with less resting, yield a higher short-term profit. However, in the long-term (over some forty years), the strategy used by the Gamis Farm was found to be superior with respect to the number of sheep. In contrast to the Stephan-Model, the aim of the present study is to deduce the basic principles for livestock-vegetation dynamics under different climatic and environmental conditions. The focus is on the value of resting pastures in a fluctuating environment and the appropriate time of resting (in wet vs. dry years) for maintaining the productive integrity of the ecosystem. We analyse whether pure restocking-destocking management strategies, without resting, are sufficient to maintain long-term productivity of the rangelands. Additionally, we determine whether the ecologically counter-intuitive strategy to rest in wet and not in dry years can be explained. To explore these issues, a simulation model is constructed. Two appropriate objective functions are defined for an assessment of the grazing strategies of interest: one with regard to the maintenance of the long-term productivity of the pasture, and a second with regard to the farmer's livelihood. Alternative grazing strategies are compared, all adapted to the available forage but differing in whether and when resting is granted for a part of the pasture.

As a result, a comprehensive understanding of the decisive mechanisms for vegetation and livestock dynamics is reached. Ecological settings are identified under which resting is necessary for the recovery of the vegetation, as well as those during which the vegetation is able to regenerate while under grazing pressure. We hypothesize that the uncriticised application of pure opportunistic strategies - destocking in times of drought and fast post-drought restocking without any resting - are insufficient in non-equilibrium systems. The emergence of unplanned rests is shown to be a crucial factor in determining the appropriate time of resting. We refer here to unintended rest periods for the vegetation, which occur after a crash of livestock numbers following a drought and the subsequent slow recovery of livestock numbers. However, the occurrence of unplanned rests depends strongly on the underlying farming system and the present infrastructure (options of livestock purchase and supplementary feeding). Finally, we can answer the question as to whether and under which circumstances this strategy, successfully used by the Gamis Farm, can be applied to other farms in semi-arid environments.

2.3 Methods

2.3.1 Study Site

Ecosystem

The Gamis Farm is situated 250 km southwest of Windhoek in Namibia (24°05'S 16°30'E) in the district Maltahöhe close to the Naukluft Mountains at an altitude of 1250 m. The climate of this arid region is characterised by low annual precipitation (177 mm/y) which is highly variable in space and time. The coefficient of variation is 56% (evaluated from annual rain data on the farm during 1979-2001). The vegetation type is classified by Giess (1998) as dwarf shrub savanna. Dominant shrub species are *Rhigozum trichotomum*, *Catophractes alexandrii*, *Acacia newbrownii* and *Leucosphaera bainesii*. The grass layer is dominated by the perennial grasses *Stipagrostis uniplumis*, *Eragrostis nindensis* and *Triraphis ramosissima*. Detailed information about climatic, edaphic and botanical setting of the study site can be found in Maurer (1995).

Gamis Strategy

Karakul sheep (race Swakara) are bred on an area of 30 000 hectares. The primary source of revenue is from the sale of lambskins. Additionally, the wool of the sheep is sold and meat is used for farm consumption (Tombrink, 1999). In good years, up to 3000 sheep are kept on the farm. For forty years, an adaptive management system has tracked the variability in forage. During this time detailed records were kept by the owner, H.A. Breiting. The basis of the system is a rotational grazing system: The pasture land is divided into 98 paddocks; A paddock is grazed for a short period (about 14 days), after which it is rested for a minimum of two months. This system puts high pressure on the vegetation for a short time to prevent selective grazing. Moreover, the farmer has introduced an additional resting: one third of the paddocks is given a rest during the growth period (September - May). Outside this period, all paddocks are grazed. In the literature this strategy is termed rotational resting (Heady, 1970, 1999; Stuth & Maraschin, 2000; Quirk, 2002).

Figure 2.1: Karakul sheep herd at a watering place on the Gamis Farm (Namibia). The pasture is degraded around the watering place. Outside this sacrifice zone the pasture is in a good ecological condition (in the back of the picture), dominated by perennial grasses of high nutritious quality due to the granting of rest periods from grazing (photo taken at the end of the dry season, 24.09.2004).

Figure 2.2: Pasture around the ephemeral river Narob in the western part of the Gamis Farm (Namibia) at the end of the dry season, 25.09.2004.

The Gamis Farm strategy is distinct from simple rotational resting systems in that rest periods are granted only in years with sufficient precipitation. In years with insufficient rainfall this rest period is reduced or completely omitted.

Further measures, such as renting of additional pasture, are taken during long periods of drought. Once a year at the end of the rainy season, the farmer decides how many of the lambs will be raised and whether additional land will be rented from farms elsewhere in the country (H.A. Breiting, pers. comm.). For a complete and detailed description of the grazing system, see Stephan *et al.* (1996, 1998a,b).

If we consider the strategy to rest in wet years from farmer's perspective, it is economically reasonable: The income made through lambskin production varies comparatively less. In years with good rain, sufficient forage is available to feed the livestock, even if a part of the pasture is rested, whilst during low rainfall years, the forage of the paddocks that would otherwise be rested is instead additionally available for the livestock. Consequently, the livestock numbers need not be substantially reduced in poor-rain years and therefore fluctuate less over a longer time horizon. This allows this sheep breeding farm to establish a regular supply of high quality furs and to limit unavoidable sale or slaughter in dry years with insufficient forage. The importance of maintaining the quality of the livestock is supported by the fact that before the Gamis farmer sells any of his Karakul sheep, the sheep destined for sale are compared with sheep in the neighbourhood. The sheep judged least valuable within the whole neighbourhood are sold and the sheep destined for sale are instead transferred to the neighbour. Hence, the high quality breeding potential is kept in the vicinity (H.A. Breiting, pers. comm.).

When considering this strategy from an ecological perspective, the farmer has recognised the importance of rest periods to regenerate the vegetation. However, allowing the rest in wet and not in dry years sounds slightly counter-intuitive. In dry years, when the vegetation has already suffered from drought, it is put under the additional stress of the higher grazing pressure. However, the condition of pasture on the farm is considered good in comparison to the neighbouring farms (Klimm *et al.*, 1994; Maurer, 1995).

2.3.2 The model

General concept

In semi-arid regions, impacts of inappropriate strategies often become visible only after decades (Briske *et al.*, 2003). Simulation models help to understand the dynamics in these landscapes, since they are able to make forecasts by using current knowledge about ecosystem processes (Wiegand *et al.*, 1995; Pickup, 1996; Wissel *et al.*, 1996; Jeltsch *et al.*, 1997; Illius & O'Connor, 2000; Weber *et al.*, 2000; Beukes *et al.*, 2002).

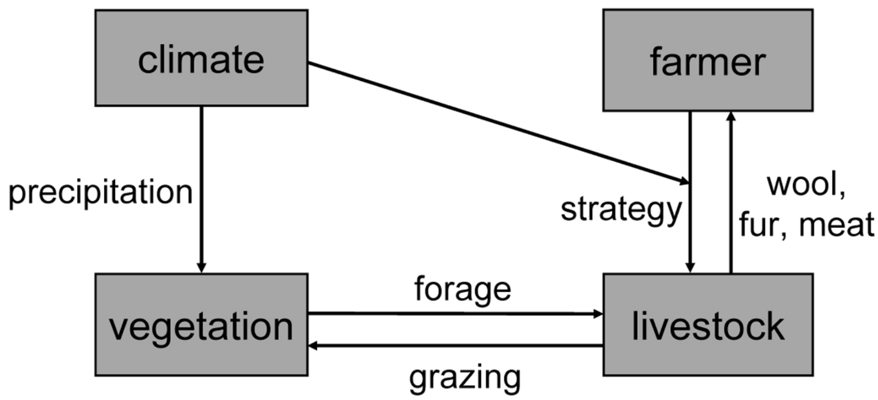

Figure 2.3: Causal diagram of the rangeland system

A detailed model of a grazed ecosystem, would not be appropriate as the objective is to gain a general understanding of whether resting is essential or not. Additionally, the complexity of a detailed model may obscure the influence of different ecological conditions making comparisons between the strategies difficult. Hence, a conceptual, highly abstract model with two relatively simple difference equations was created. Spatial aspects were considered only implicitly and details that were felt to be unimportant for a general understanding were omitted. The model is time discrete with annual time steps. This time frame is appropriate as there is a single rainy season per year, following which the farmer adapts the livestock number to the available forage. As on the Gamis Farm, the pasture in the model is divided into paddocks with the dynamics of each paddock modelled separately.

Structure of the model

In developing this abstract, conceptual model, the main driving processes of the studied system were first identified (Figure 2.3). Four principal components drive the dynamics of the vegetation in a semi-arid savanna: (1) plant-available water, (2) plant-available nutrients, (3) fire and (4) grazing (Skarpe, 1992). Natural fires do not occur in this type of ecosystem (H.A. Breiting, pers. comm.). In savanna systems with low rainfall (below 200-300 mm), the vegetation is to a greater extent limited by water than nutrients (Le Houérou, 1989; Snyman & Fouché, 1991), and differences in plant-available nutrients resulting from different soil conditions were not explicitly simulated in the model. The importance of the role that nutrients play in vegetation dynamics is not doubted, rather the philosophy of the approach was to include only aspects that are crucial for answering the underlying questions, while other factors were treated only implicitly. Accordingly, of the four components mentioned driving vegetation dynamics, only precipitation and grazing were explicitly included in the model.

The economic viability of alternative strategies was assessed from the number of livestock on the farm. The livestock constitutes the basis of the farmer's existence. On the Gamis Farm, the farmer earns his living via the revenue from sale of lambskins and sheep wool. The number of livestock on the farm depends on the chosen management strategy; for example, if the farmer embarks on the strategy "resting in wet years", rainfall determines whether some paddocks are rested. In addition, the livestock number is adjusted to the available forage. The surplus of livestock are slaughtered or sold. Hence, in this case, both vegetation and precipitation are key factors in determining the stocking rate.

Model components in detail

Vegetation dynamics (1) Terms green biomass and reserve biomass: The life history of the different vegetation types and their reaction to grazing and browsing is quite diverse (Noy-Meir, 1982). However, initially a single abstract perennial vegetation type was modelled. A central task of the model is to represent the response of the vegetation to precipitation and grazing. The dynamics of the vegetation are not only influenced by the current precipitation but also to large extent by the plant reserves, as determined by the rain history i.e. the precipitation of preceding years (Figure 2.4 and O'Connor & Everson, 1998). Hence, two characteristics of the vegetation were differentiated (Stephan *et al.*, 1998a): firstly, the green biomass G, describing the photosynthetic organs of the plant and being the part of the plant which serves as forage for the livestock; secondly, the reserve biomass R (termed after Noy-Meir (1982)), describing the non-photosynthetic reserve organs below or above ground. It follows that both rain and grazing history of the vegetation is reflected by the reserve biomass. Stephan *et al.* (1998a) and Weber *et al.* (2000) use similar terms for reserve biomass - vital biomass and potential production respectively.

(2) Dynamics of green biomass: The current precipitation has a considerable influence on the production of green biomass (Figure 2.4). As mentioned previously, precipitation in arid regions is characterised by a low mean but high spatial and temporal fluctuation. To simulate these properties as a stochastic process, a log-normal distribution of the annual rainfall is effective (Sandford, 1982). It is a right-skewed distribution: events with low rainfall are frequent, but single high-rainfall-events also occur. Not all water is available for plant growth, due to evotransporation and run-off processes. Hence, in the model only the portion of precipitation that is available for the plants, indicated by the measure p_t, was incorporated. Intra-annual fluctuations of precipitation, which influence to a high

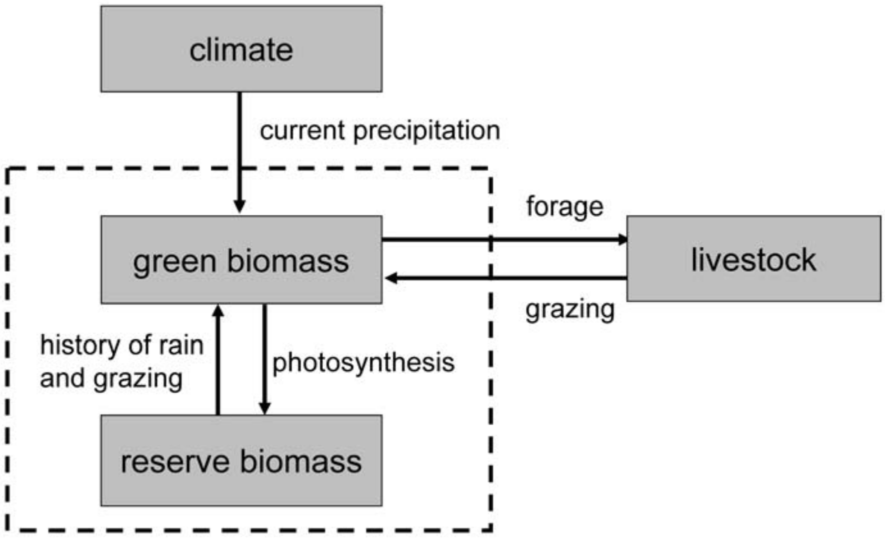

Figure 2.4: Causal diagram of vegetation dynamics

degree the germination and establishment of grasses, were not modelled explicitly to reduce the complexity of the model. Apart from the current precipitation, the available plant reserves strongly influence the formation of new green biomass G. Hence, a multiplicative interrelation between the reserve biomass R and the current precipitation was assumed. The growth dynamics of the green biomass G_t^i of paddock i in time step t were defined by:

$$G_t^i = w_{gr} \cdot p_t \cdot R_t^i \qquad \text{for} \quad i = 1, \ldots, n \quad \text{and} \quad t = 1, \ldots, T, \qquad (2.1)$$

with n denoting the number of paddocks and T the time horizon. The parameter w_{gr} is a conversion parameter, indicating the extent to which the green biomass G_t^i responds to the reserve biomass R_t^i and current plant-available water p_t. The factor w_{gr} is subsequently referred to as the growth rate of green biomass.

(3) Dynamics of the reserve biomass: The generation of new reserve biomass R_{t+1} in year $t + 1$ was assumed to be the result of photosynthesis and hence dependent on the available green biomass G_t in time step t. The extent to which new reserve biomass R_{t+1} is accumulated from green biomass G_t by photosynthesis is described in the growth rate of reserve biomass w_{res} (see Equation 2.2). In the current model, it was assumed that grazing only affects the green biomass G_t and has no direct influence on reserve biomass R_t (Figure 2.4). So for instance, the effect of animals pulling out entire grass tufts in dry years is ignored. This simplification is justifiable, because the stocking rate S_t is closely adjusted to the available forage G_t. Nevertheless, grazing has an indirect influence on reserve biomass R_{t+1}, because

less storage may be built up by photosynthesis if the paddock is grazed. In reality, the impact of grazing strongly depends on several factors, for example on the time of grazing during the year. To take into account these aspects a coefficient c was introduced, which expresses the extent to which a grazed paddock can build up new reserve biomass R_{t+1} by photosynthesis. This coefficient c is called the "harshness of grazing", which describes the reduction in vegetation growth under grazing. It is assumed to take values between zero and one. The higher the value of parameter c the less green biomass is available for the production of reserve biomass. The impact of grazing on the regeneration of the vegetation is then high ($R_{t+1} = w_{res} \cdot (1-c) \cdot G_t$).

Besides the described build-up process of the reserve biomass R_{t+1}, the consumption process has to be included. In this model, the reserve biomass R_t decreases with a constant consumption rate m describing the use of reserves to maintain the vital functions of the plant. The vegetation dynamics were modelled for each paddock separately and afterwards summarized to determine the state of the pasture and the available forage. For a given paddock i, the annual dynamics of the reserve biomass R^i_{t+1} it can be described by:

$$R^i_{t+1} = \begin{cases} (1-m) \cdot R^i_t + w_{res} \cdot (1-c) \cdot G^i_t & \text{if } i \text{ is grazed}, \quad 0 \leq c \leq 1 \\ (1-m) \cdot R^i_t + w_{res} \cdot G^i_t & \text{if } i \text{ is rested} \end{cases} \tag{2.2}$$

The equation holds for all time steps t, $t = 1, \ldots, T$, and for all paddocks i, $i = 1, \ldots, n$. T indicates the chosen time horizon in years and n the number of paddocks on the farm, G^i_t the corresponding green biomass on paddock i, c the harshness of grazing and m the consumption rate of the vegetation. Equation 2.1 inserted in Equation 2.2 describes the vegetation dynamics solely dependent on the variable reserve biomass R^i_t.

(4) Density dependence: In order to include density dependence, a corresponding parameter d was introduced. The reserve biomass R^i_{t+1} in paddock i in time $t+1$, depends on the reserve biomass R^i_t in the previous time period, reduced by a consumption term and increased by a growth term. The higher d the higher the consumption and the lower the growth:

$$R^i_{t+1} = \begin{cases} R^i_t \cdot ((1-m) \cdot (1 + d \cdot R^i_t) + w_{gr} \cdot w_{res} \cdot p_t \cdot (1-c) \cdot (1 - d \cdot R^i_t)) \\ R^i_t \cdot ((1-m) \cdot (1 + d \cdot R^i_t) + w_{gr} \cdot w_{res} \cdot p_t \cdot (1 - d \cdot R^i_t)) \end{cases} \tag{2.3}$$

if paddock i is grazed/rested, respectively ($0 \leq c \leq 1$).

Equation 2.3 reveals that only the product of the two growth rates of the vegetation, w_{gr} and w_{res}, is crucial for the dynamics. A new parameter, the effective growth rate of vegetation w_{eff} ($w_{eff} = w_{gr} \cdot w_{res}$), was introduced.

Stocking rate A basic assumption of the model is that every year the stocking rate S_t of the livestock tracks the available forage G_t, or more accurately, the available forage in the paddocks not reserved for resting G_t^{avail}. The surplus of livestock is sold or slaughtered. The dynamics of the flock size are determined by the growth rate of livestock b. Only ewes were included; the number of rams was ignored, because the majority of male lambs are slaughtered just after birth. Purchase of livestock was excluded to maintain the purity of breeding stock. The current stocking rate S_t is therefore limited by two factors: first by the total available forage not reserved for resting, G_t^{avail}, and secondly, by the internal growth of the livestock flock $(b+1) \cdot S_{t-1}$. It was assumed that livestock are sold at the age of seven years, indicated by S_t^{old}. The age of the livestock was recorded within a simulation run. In Equation 2.4, this relationship is formulated:

$$S_t = \min\left((b+1) \cdot S_{t-1} - S_{t-1}^{old}, G_t^{avail}\right) \tag{2.4}$$

Management strategies All the management strategies contrasted have in common the previously-described short-term adaptation to the available forage. They differ only as to whether and when additional resting is granted. The following four strategies were investigated:

1. No resting takes place ("without resting").
2. In each year, a third of the paddocks is rested ("always resting").
3. In wet years, one third of the paddocks is rested. In dry years, all paddocks are grazed ("resting in wet years").
4. In dry years, one third of the paddocks is rested. In wet years, all paddocks are grazed ("resting in dry years").

In order to distinguish between wet and dry years, a threshold had to be defined. For the first step, the median of the rainfall distribution was chosen. Consequently, years above the threshold (so called "wet years") occur equally often as years below the threshold (so called "dry years"). This allows the investigation concerning the appropriate time of resting to be made more easily, since the portion of years with resting is the same for both strategies: fifty percent. In the present model, the paddocks with the lowest reserve biomass were always selected for resting first.

Objective functions Sustainable land use is the criteria by which the different grazing strategies were assessed. The definition of sustainability that is most relevant for this purpose poses a point of discussion. Pickup & Stafford Smith (1993) include in their definition such activities that maintain the long-term productivity of the vegetation whilst simultaneously providing sufficient financial and non-financial income for manager and employees. We follow this approach, because it reflects our objectives to consider both ecological and economic aspects with equal weight. The variable green biomass G_t is a poor indicator for the long-term quality for the vegetation. Current precipitation strongly influences available forage and, grazing reduces the current green biomass on the farm. The attribute reserve biomass R_t on the other hand more effectively reflects the long-term consequences of precipitation and grazing. Hence, this trait was chosen to assess the ecological condition of the farm. Revenue made by the farm is largely from the sale of lambskins and sheep wool. For both the ewes are integral and it was assumed that the income of the farmer is proportional to the number of livestock S_t kept on the farm. In this simple case, it was assumed that the farmer has no preferences in time. That means that current revenues have the same value as revenues in the future. Consequently, the two objective functions to be maximized are the mean reserve biomass R_{mean}, and the mean livestock number S_{mean}, where the average is taken over the time horizon T.

Simulation

The interaction of vegetation and grazing was simulated for a time horizon T of 100 years. First, 100 years of vegetation dynamics without grazing were run. This time span was used to minimize the influence of initial conditions of vegetation R_0 on the dynamics. Due to the high level of abstraction, the parameters used in the model were not chosen to reflect exactly the real farm, but for providing a better understanding of underlying dynamics. The default parameter-set is shown in Table 2.1. Where not mentioned to the contrary, this set is used during the following simulations.

2.4 Results

2.4.1 To rest or not to rest

The first part of the study compares Strategy 1 ("without resting") and Strategy 2 ("always resting") in a fluctuating environment. The effective growth rate of vegetation w_{eff} was found to heavily influence the dynamics. At first, the mean reserve biomass R_{mean} was analysed in relation to w_{eff}, holding the rest of the

Table 2.1: Default parameter set of the simulation

Parameter		Value
Mean of precipitation	$E(p_t)$	1.2
Standard deviation of precipitation	$\sigma(p_t)$	0.7
Effective growth rate of vegetation	w_{eff}	0.22
Consumption rate of reserve biomass	m	0.15
Growth rate of livestock	b	0.8
Initial total cover of reserve biomass	R_0	4000
Harshness of grazing	c	0.5
Density dependence of reserve biomass	d	0.000125
Number of paddocks	n	60
Number of simulations	s	1000
Time horizon in years	T	100

parameters constant (Figure 2.5). As expected, resting results in a higher R_{mean} than not resting, for each value of w_{eff}.

However, regarding the mean livestock number S_{mean} the findings are more differentiated (Figure 2.6a). Three different stages are revealed. For low effective growth rate of vegetation w_{eff} (below 0.15), S_{mean} is very low, i.e. the pasture is not capable of supporting livestock, regardless of the chosen strategy. When a high growth rate of the vegetation (w_{eff} above 0.34) is considered, S_{mean} is higher without resting. Resting is dispensable since the recovery capacity is high enough to compensate grazing impacts. However, in an intermediate range of w_{eff} , resting leads to higher values of the economic objective criterion S_{mean} than the strategy without resting. The relative difference between the adaptive Strategy 2 ("always resting") and the adaptive Strategy 1 ("without resting") is calculated by:

$$\frac{S_{mean}^{Strategy2} - S_{mean}^{Strategy1}}{S_{mean}^{Strategy1}}. \tag{2.5}$$

With an effective growth rate of vegetation $w_{eff} = 0.2$, about 25% more livestock can be supported by the farm when applying the strategy with resting (770 livestock) in comparison to the strategy without resting (616 livestock) (Figure 2.6b). This difference is of high economic importance.

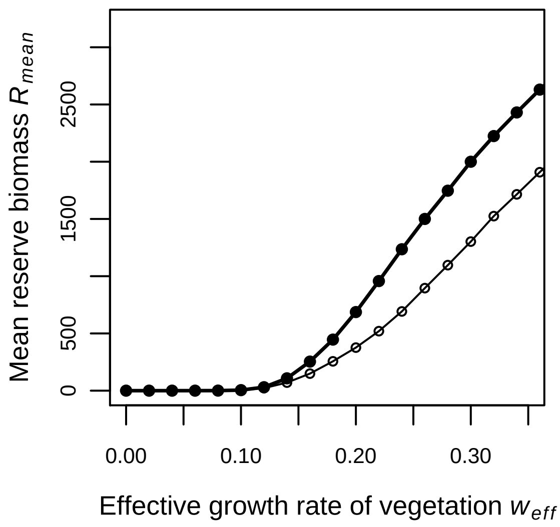

Figure 2.5: Mean reserve biomass R_{mean} over 100 years versus effective growth rate of vegetation w_{eff}, compared for the adaptive strategy with resting (•) and the adaptive strategy without resting (○).

Beside the effective growth rate of vegetation w_{eff} , a second parameter turned out to be crucial: the harshness of grazing c represents the extent to which grazing influences the regeneration of the vegetation. Analyses not presented here, indicated that a variation of parameter c shifts the threshold in Figure 2.6a, above which the strategy without resting becomes superior. In detail: Reducing c below 0.5 (low impact of grazing) shifts the threshold in Figure 2.6a to the left. This implies that even at a lower value of w_{eff} the strategy without resting becomes superior. In contrast, increasing c above 0.5 (high impact of grazing) moves the threshold to the right. Hence, the strategy without resting becomes superior only for a higher value of w_{eff}. However, the qualitative behaviour of the dynamics does not change as the parameter c, the harshness of grazing, is varied.

2.4.2 Why resting in wet years?

The farmer on the Gamis Farm applies a more sophisticated strategy than simply resting a third of the paddocks; instead he permits the rests only in years with sufficient rainfall. The simulation model was used to analyse the state of the vegetation under the two strategies "resting in wet years" and "resting in dry years". Surprisingly, regardless of the effective growth rate w_{eff}, the strategy to rest in wet years maintains the reserve biomass R_{mean} at a higher level, compared to the strategy to rest in dry years (Figure 2.7a). The growth rate of livestock b

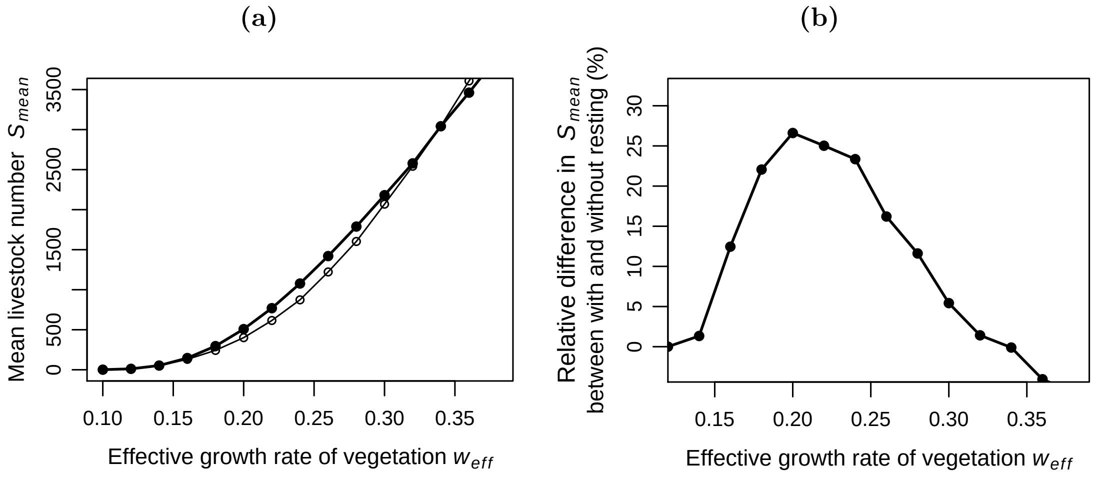

Figure 2.6: (a) Mean livestock number S_{mean} over 100 years versus effective growth rate of vegetation w_{eff}, compared for the adaptive strategy with resting (•) and the adaptive strategy without resting (∘). (b) Relative difference in mean livestock number S_{mean} (denoted in percent) resulting from strategies - with and without resting.

was set at first to a high value of 3. A small calculation, comparing both strategies, explains the result. To make it simpler, the effect of density dependence d in Equation 2.3 is ignored ($d = 0$). Let us assume, a dry year, $t = 1$, is followed by a wet year, $t = 2$ ($p_1 < p_2$). Applying resting in dry years, the first year $t = 1$ is rested. In the second case, resting takes place in the second year. After two years, starting from the same initial reserve biomass R_0, the reserve biomass applying "resting in dry years" (R_2^{dry}) and "resting in wet years" (R_2^{wet}), respectively, can be expressed by:

$$
\begin{aligned}
R_2^{dry} &= \big((1-m) + w_{eff} \cdot (1-c) \cdot p_2\big) \cdot R_1^{dry} \\
&\qquad\qquad \text{with} \quad R_1^{dry} = \big((1-m) + w_{eff} \cdot p_1\big) \cdot R_0 \\
R_2^{wet} &= \big((1-m) + w_{eff} \cdot p_2\big) \cdot R_1^{wet} \\
&\qquad\qquad \text{with} \quad R_1^{wet} = \big((1-m) + w_{eff} \cdot (1-c) \cdot p_1\big) \cdot R_0
\end{aligned}
\tag{2.6}
$$

Subsuming both equation systems and transforming, $R_2^{wet} > R_2^{dry}$ is obtained, as $p_2 > p_1$. This result is independent of the order in which wet and dry years occur.

With respect to the mean livestock number S_{mean}, three different ranges of effective growth rate w_{eff} occurred, similar to the preceding analysis comparing the livestock number under resting and without resting (without figure). For a low effective growth rate w_{eff}, no livestock can be supported regardless of the chosen

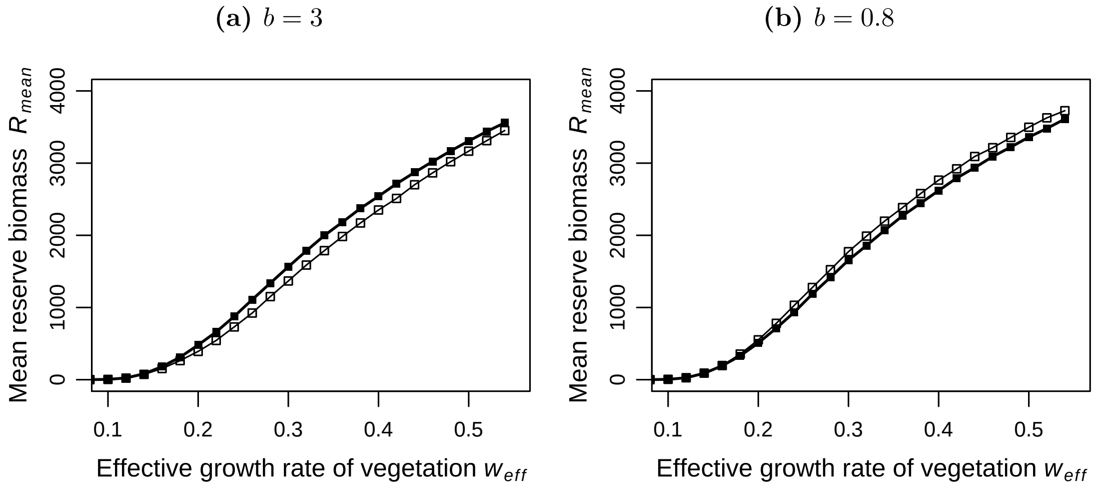

Figure 2.7: Mean reserve biomass R_{mean} versus effective growth rate of vegetation w_{eff} comparing "resting in wet years" (■) and "resting in dry years"(□), for two different growth rates of livestock b.

strategy. For high w_{eff}, the vegetation is able to buffer the impacts of grazing. Consequently, vegetation is not a limiting factor. Therefore, those of both strategies ("resting in wet years" and "resting in dry years") has to be selected, for which more livestock is held. This is "resting in dry years" - completely utilising the available forage during the highly productive wet years. However, in an intermediate range, "resting in wet years" leads to higher mean livestock number S_{mean} than "resting in dry years".

Apart from the growth rate of the vegetation w_{eff}, the reproductive rate of the livestock b strongly influences the dynamics. Setting $b = 0.8$, resulted in the previously superior strategy of "resting in wet years" with respect to mean reserve biomass R_{mean}, to no longer be so, for all w_{eff} (Figure 2.7b). This result stimulated a systematic investigation of the influence of the growth rate of the livestock b on the objective functions. The effective growth rate of vegetation w_{eff} was held at an intermediate level ($w_{eff} = 0.22$). It appears that a critical value of the growth rate of livestock ($b = 1.1$) exists above which "resting in wet years" is superior to "resting in dry years" with respect to mean reserve biomass R_{mean} (Figure 2.8a). Below this threshold, the opposite is true.

The mean livestock number S_{mean} was determined for different growth rates of livestock b (Figure 2.8b). Regarding the "resting in dry years" strategy, the livestock number is higher when b is low than when b is high. The reason for this trend is that the condition of the pasture is crucial for S_{mean}. The same effect is

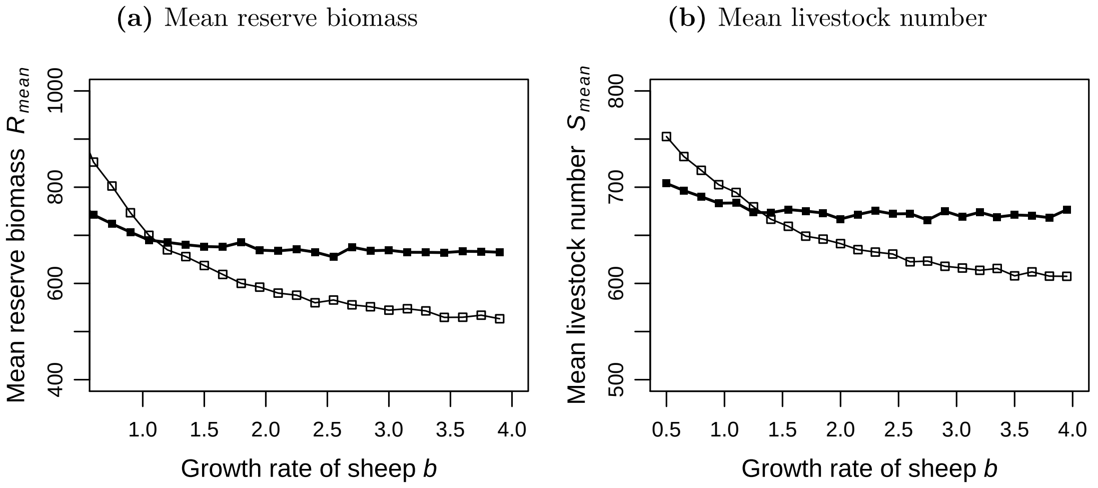

Figure 2.8: (a) Mean reserve biomass R_{mean}, (b) Mean livestock number S_{mean}. Both variables mapped in relation to growth rate of of livestock b for "resting in wet years" (■) and "resting in dry years" (□), number of simulations $s = 400$.

apparent when both strategies are compared: For each value of b, a strategy is superior with respect to S_{mean}, whenever it is also superior with respect to the mean reserve biomass R_{mean} (in case of b low: "resting in dry years", in case of b high: "resting in wet years").

2.5 Discussion

2.5.1 Resting - relevant for non-equilibrium systems

This study contributes to the theoretical debate of the appropriateness of opportunistic strategies versus planned measures in human utilised (semi-) arid ecosystems. In the current literature, the recommendation for non-equilibrium systems is to adjust livestock numbers closely to available forage (Behnke Jr & Kerven, 1994). This is considered the most appropriate strategy to prevent degradation in a highly fluctuating environment. However, the analysis presented here supports the idea that there are no universally applicable grazing strategies, because particular context-specific conditions have to be taken into account (Scoones, 1994). It is shown that measures targeted for the long term, such as resting a part of the pasture, may also be relevant in non-equilibriums systems (in contrast to a statement made by Oba *et al.*, 2000). Admittedly, when vegetation is assumed to have a high reproductive potential (high effective growth rate of vegetation w_{eff} and small harshness of grazing c), resting is not necessary from an ecological point of view and is economically counter-productive. Nevertheless, under certain conditions (low effective growth rate of vegetation w_{eff} and high harshness of grazing c , grazing has a high impact and this strategy of "seizing opportunities when and where they existed" (Scoones, 1994, p.9) does not allow the vegetation to recover: rest is needed. In this case, resting accelerates improvements in range condition (Tainton & Danckwerts, 1999) and allows a higher total stocking rate within a certain time period (Quirk, 2002).

2.5.2 The appropriate time of resting

The investigation of the appropriate time of resting (during wet years or dry years) with respect to the ecological and economic objective criterion (mean reserve biomass R_{mean} and mean livestock number S_{mean}) has shown that no universally superior strategy exists. Two parameters of the system, the effective growth rate of vegetation w_{eff} and the growth rate of livestock b, are the key factors. Tables 2.2 and 2.3 represent the results of the qualitative influence of these two parameters. For each combination of the two parameters, the reason for the superiority of one of the two strategies will be carefully analysed in the following paragraphs.

Ecological objective criterion - mean reserve biomass

Assuming the growth rate of livestock b to be low (Table 2.2, column 1): After a drought and subsequent reduced livestock number, the available green biomass G_t^{avail} exceeds the required forage. Hence some paddocks are not used and effectively (unplanned) rested. These unplanned rests occur to a higher degree under "resting in dry years", as during the years of drought the stock numbers are reduced for two reasons: insufficient forage and the rule to rest a third of the paddocks. This "breath" for the vegetation in post-drought years leads to a better overall condition of the pasture. Therefore, in this case, "resting in dry years" is favourable with respect to the mean reserve biomass R_{mean} (Table 2.2: r1/c1, r2/c1). For a further discussion of unplanned rests see below.

Assuming the growth rate of livestock b to be high (Table 2.2, column 2): After a drought, the increase in the livestock number is fast. Unplanned rests for the vegetation do not occur, regardless of the chosen grazing strategy. Consequently, both strategies have the same frequencies of resting (only planned resting) but differ in the time of resting. Counter to intuitive thinking that the vegetation has to be spared in years of drought, the model results reveal that the granting of rests during wet years is crucial for the regeneration of the pasture. In dry years, the vegetation barely benefits from resting. There is too little water available to build up new reserve biomass by photosynthesis. Hence, grazing in dry years has little impact on vegetation (Sullivan & Rohde, 2002). In contrary, when resting

Table 2.2: Superior strategy with respect to mean reserve biomass R_{mean} in dependence of growth rate of livestock b and effective growth rate of vegetation w_{eff} ("wet" indicates "resting in wet years" , dry - "resting in dry years")

Objective: Mean reserve biomass			
		Growth rate livestock	
		low	high
Growth rate vegetation	low	dry	wet
	high	dry	wet

is allowed in a wet year, the vegetation is able to exploit the higher amount of precipitation in photosynthesis to build up new reserve biomass. To summarize, the simultaneous incidence of a high amount of available water and resting was found to be crucial for vegetation regeneration.

This issue has seldom been explicitly investigated in the rangeland literature. Although Danckwerts & Stuart-Hill (1988) emphasise the importance of resting in post-drought years "to facilitate rapid recovery after a drought" (Danckwerts & Stuart-Hill, 1988, p.218), they do not acknowledge the value of resting in wet years in general. More frequent investigations have been made into a similar aspect: Resting during the wet season of a year enables flowering, seed production, and biomass production (Tainton & Danckwerts, 1999; Oba *et al.*, 2000).

Economic objective criterion - mean livestock number

When assessing the economic objective criterion one has to bear in mind, which one of the two growth rates is low, and therefore limiting the dynamics (Table 2.3).

► w_{eff} low (Table 2.3: row 1): Here the livestock production is limited by the low regeneration potential of the reserve biomass R_{mean}. Hence, a strategy needs to be chosen that will allow higher mean livestock numbers S_{mean}, by being superior with regard to R_{mean} (cf. Table 2.2) - in the case of low growth of livestock b "resting in dry years", in the case of high b "resting in wet years".

► w_{eff} high, but b low (Table 2.3: r2/c1): The low regeneration potential of the livestock is limiting. Management needs to focus on maintaining the minimal number of livestock as high as possible. Consequently, the strategy that encourages the smallest reduction of livestock numbers in dry years is superior. "Resting in wet years" is preferential, because in this case rested paddocks are disposable for forage in dry years.

Table 2.3: Superior strategy with respect to mean livestock number S_{mean} in dependence of growth rate of livestock b and effective growth rate of vegetation w_{eff} ("wet" indicates "resting in wet years" , dry - "resting in dry years")

Objective: Mean livestock number			
		Growth rate livestock low	high
Growth rate vegetation	low	dry (reason: unplanned rests occur)	wet (reason: resting in rainy years more efficient for regeneration of vegetation)
	high	wet (reason: decline of livestock number in dry years less)	dry (reason: higher stocking in rainy years is possible)

► No limiting parameters (w_{eff} high, b high) (Table 2.3: r2/c2): The farmer chooses those strategies which enable the highest amount of livestock to be supported on the farm. The pasture should not be rested in a wet year but rather fully grazed with "resting in dry years" being more effective. Obviously, the best strategy would be to never rest.

The question arises as to the range of the parameters used for the Gamis Farm (Tables 2.2 and 2.3). Considering the underlying arid climate, the effective growth rate of vegetation w_{eff} can be classified as low. However, long-term establishment is possible. Hence, resting is an essential part of the system. With $b = 0.8$ (or 0.4 when considering only the females) the growth rate of the livestock on the farm is low. According to Tables 2.2 and 2.3 "resting in dry years" should be applied. This contradicts the strategy applied on the farm. However, the inclusion of additional drought-coping measures, like renting of pasture, changes the result. Renting leads to comparably high livestock pressure on the vegetation, evident in the first year following drought, and non-planned rests do not occur. Consequently, the Gamis Farm is classified to have low vegetation growth but relatively high livestock growth and Tables 2.2 and 2.3 indicate "resting in wet years" to be an effective strategy.

Thus, the farmer on the Gamis Farm applies a flexible strategy, combining short-term adaptation of the stocking rate with measures targeted for the long term such as resting a third of the paddocks in years with sufficient rainfall. This strategy is able to maintain a more constant income when compared to an opportunistic strategy without resting. Hence, the negative consequences of highly unpredictable and variable environments can be avoided or lessened. These include transaction costs resulting from low livestock prices in times of drought in contrast to higher values in post-drought times (Campbell *et al.*, 2000; Toulmin, 1994), as well as reduced transport availability and restricted livestock-markets.

It remains to be established how large a farm needs to be for a part of the pasture to be rested, whilst sustaining a viable livelihood - a problem that applies particularly to communally-owned land in Africa.

The study has shown that not only economic measures are able to buffer environmental variability (contrary to Behnke Jr & Kerven, 1994), but also the vegetation itself. So the general assumption of Sandford (1982, p.67), that "nor overgrazing or undergrazing in one year affect, favourably or adversely, productivity ... in subsequent years" is doubted. Maurer (1995), referring to the study site Gamis Farm, confirms that deficits of precipitation may be buffered by biomass reserves of preceding years. Here unplanned rests play a significant role.

Rest periods - the role of the farming system

Whether resting is carried out by planned or unplanned measures depends on the farming system. On commercial farms, this repose is obtained primarily through planned rotational resting. If subsistence farming is carried out, a differentiation has to be made between (a) application of de- and restocking strategies (by sale and purchase) tracking the climate and (b) climate induced die-off and slow recovery of the livestock for herders with limited access to livestock markets. In the second case, without the purchase of livestock, the regeneration of the reserve biomass is stimulated in post-drought years because of the slow increase of livestock. These non-planned rests are of high importance, as shown in the present study.

In the literature, however, the distinct ecological consequences of the two strategies are very rarely explicitly considered (although cf. Toulmin, 1994; Briske *et al.*, 2003). Both strategies ((a) de- and restocking and (b) die-off and slow recovery) are referred to as "opportunistic", often treated in the same way and not distinguished between (Sandford, 1982; Bartels *et al.*, 1993; Behnke Jr *et al.*, 1993). Sandford (1994, p.175) terms version (a) even "efficient opportunism" without mentioning any ecological consequences. Toulmin (1994) in contrast highlights the pros and cons of slow recovery of livestock numbers resulting from strategy (b). She mentions the need for a given time period for recovery from drought for certain ecosystems, yet acknowledges the social implications of the "waste of grazing resources" if there is a prolonged absence of grazing. In particular, if farmers change from strategy (b) to strategy (a), for instance as a result of improved access to livestock markets, they need to be aware of the effects of discontinuing unplanned rests. The long-term consequences for the condition of the vegetation and for the number of livestock that can be held on the farm, must be explicitly considered. It stands to reason that this issue should also be kept in mind by political decisions makers.

Similar consequences occur when supplementary feeding is carried out (Illius & O'Connor, 1999). This measure has been prescribed by the New Rangeland Science as being suitable to cope with droughts (Scoones, 1994; Toulmin, 1994). However, the ecological consequences are not considered. Under this strategy, the stocking rate is held at a high level in dry years. Consequently, the vegetation receives no respite in post-drought years by unplanned resting. The blind support of supplementary feeding is therefore strongly questionable. Only Briske *et al.* (2003) stresses the adverse impact of supplemental feeding and other management options on vegetation dynamics.

Final remark: this conceptual model depicts and examines a highly simplified representation of the real Gamis Farm. Its application to concrete management support is therefore limited. However, conceptual simplifications are essential for range management (Stafford Smith, 1996). By focusing only on the main characteristics of the dynamics, and through systematic analysis, the basic principles regarding the value of resting in a fluctuating environment could be detected. In taking this approach, a contribution to the present discussion surrounding the existing paradigms in rangeland science has been made.

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2.7 Link to the proceeding chapter

This chapter (2) focused on the relevance and functioning of pasture resting for sustainable grazing management in semi-arid regions. To support such an assessment, an ecological simulation model was constructed based on the successful management system of the Gamis Farm (Namibia). Integral to this management system is the resting of a third of the pasture during years with sufficient rainfall. The analysis revealed that resting during wet years is crucial to maintaining pasture productivity in systems with low regeneration potential. The ecological model forms the base for an ecological-economic model presented in the following chapter (3). I focus on whether a farmer, who has access to economic institutions of risk management, applies less conservative strategies than a farmer without access. In particular, I consider rain-index insurances, as one form of economic institutions. These are insurances where a payout is granted whenever precipitation falls below a prior specified threshold. In contrast to the Gamis-Strategy (resting of a third of the pasture in years with sufficient rainfall), a range of strategies with different sizes of rested pastures and rain thresholds is considered. In this analysis, the feedback mechanisms between the ecological and economic factors are explicitly included.

3 Risk management in a semi-arid rangeland system - the role of rain-index insurances[1]

3.1 Abstract

The livelihood of a vast majority of people in (semi-)arid regions depends on livestock farming. Inappropriate grazing strategies can lead to degradation, i.e. loss of pasture productivity. Moreover, the highly variable and uncertain precipitation translates into a highly unpredictable income. Rain-index insurance provides the possibility of reducing income variability. The advantage of this type of insurance is that it avoids classical insurance problems such as moral hazard and adverse selection because payout does not depend on an individual farmer's behaviour.

This study investigates how the introduction of rain-index insurance influences the grazing strategy of a farmer. The hypothesis tested is that when insurance is available, risk-averse farmers employ less conservative strategies and, therefore, degradation of the rangeland is accelerated.

The starting point for the analysis of different grazing strategies is an ecologically and economically successful farm in Namibia. With the help of an ecological-economic model, the farmer's choice of a grazing strategy with and without insurance is compared. The decision criterion applied is a safety-first rule: the primary goal being to reach a certain minimal income. The impact of the resulting grazing strategy on the long-term productivity of the pasture is investigated.

The first part of the analysis (without access to insurance) shows that a grazing strategy that adapts livestock number to the available forage, but ensures rest periods for a portion of the pasture during rainy years, is risk-reducing. It buffers income variability for the short term and ensures high pasture productivity over the long term.

In the second part, the factors are revealed which influence whether a farmer with access to insurance will change the grazing strategy: the farmer's preferences and, in particular, the risk aversion and the time horizon. For long-term thinking

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farmers, resting is an important part of the management system in order to maintain the productivity of the pasture. However, risk-averse farmers who think in short-term apply less conservative grazing strategies with access to insurance than without, since the insurance is able to buffer income losses in dry years. Whether reduced resting leads to a degradation of the pasture is shown to depend on the underlying ecological and climatic conditions.

Policy makers should be aware of the influence of economic risk management measures, such as insurances, on farmer's choice of grazing strategies, since they may have detrimental affects on the productivity of the rangeland ecosystem. Therefore, an analysis including explicitly ecological and economic feedback mechanisms of the land use system is a prerequisite.

3.2 Introduction

3.2.1 How to cope with risk in semi-arid regions

A third of earth's land surface consists of (semi-)arid regions. The livelihood of a vast majority of people in these areas is earned by livestock farming. Due to the highly variable and uncertain precipitation the income gained by livestock farming is very risky. Catastrophic livestock losses resulting from long lasting droughts threaten particularly subsistence farmers in those regions where economic institutions for risk management are scarcely available (Hazell, 1992; Nieuwoudt, 2000).

In the USA for over one hundred years crop insurances are offered in agriculture to manage risk. Farmers who have contracted such insurance receive a payment depending on the experienced loss. The asymmetric information distribution of farmers and insurance enterprises leads to classical insurance problems such as moral hazard and adverse selection (for an example see Luo *et al.*, 1994). Additionally, sufficient and reliable historical data of farm yields are often not available to calculate a fair insurance premium. In order to cope with these problems, insurance premiums have to be either extremely high or highly subsidized by the government. Hence, in the vast majority of cases, agricultural insurances are not profitable and if they are, private insurers serve predominantly large-scale commercial farms growing high-value crops (Hazell, 1992).

One method for avoiding these classical insurance problems is to offer index-based insurances (Skees & Barnett, 1999). The payout of the insurance does not depend on individual farmer's behaviour, but on an index on the prior specified area. Two forms are distinguished (Hazell, 1992; Miranda & Vedenov, 2001): area-yield indices and rain indices. In the first case the payout is granted when the livestock yield on a regional scale does not reach a prior specified limit (Miranda, 1991; Skees *et al.*, 1997). In the second case, the insurance pays out whenever a predetermined precipitation level is not reached. Thus for index-based insurances no data at the farm level are required.

Since the income of livestock farming in semi-arid regions is, in most cases, strongly correlated to the annual precipitation, the focus in this study is set on the second form of index-based insurances - on rain-index insurances.

3.2.2 Appropriate measure: Rain-index insurances

Currently, numerous studies by the World Bank are being carried out worldwide to investigate the feasibility of rain-index insurances, for instance in Morocco, Mexico, Nicaragua, Uruguay (Skees & Barnett, 1999; Miranda & Vedenov, 2001; Skees *et al.*, 2002; Wenner & Arias, 2003). In Morocco and Nicaragua pilot projects are already in the phase of implementation (Hess *et al.*, 2002; McCarthy, 2003). In Ontario (Canada) rainfall insurances have been in practise since 2000 (Turvey, 2001).

This type of insurance has been highly investigated recently in literature: Studies exist which deal with the issue of developing and pricing such a form of rain-index insurances (Martin *et al.*, 2001), designing optimal insurance contracts (Mahul, 2001) or empirical studies which are aimed at estimating the demand for them (Patrick, 1988; Sakurai & Reardon, 1997).

Investigations have shown that rain-index insurances are an attractive alternative to traditional insurances which face high transaction costs (Skees & Barnett, 1999; Miranda & Vedenov, 2001). The design of these insurance contracts, based on trigger rain events which are simple, independent of farmer's behaviour, difficult to manipulate, transparent, and easy to monitor, involves numerous advantages: The simple form of the contracts raises the acceptance in areas where farmer are less educated. It can be tailored to the specific needs of the customers (Skees & Barnett, 1999; Turvey, 2001). Secondly, problems resulting from asymmetric information such as moral hazard and adverse selection can be avoided. Thirdly, the transparency of index-based contracts and their independence from major financial markets both make the contracts attractive for foreign investors and allow insurers to transfer the systemic component of insurer's risk to the global market (Miranda & Vedenov, 2001). These authors, furthermore, point out the additional advantage that agribusinesses, which are indirectly affected by weather risk, may also contract such forms of insurance policies as input supply, transportation, storage, processing, marketing, banks, governments.

Nevertheless, certain challenges have to be mentioned: This form of insurance is only suitable where income risk is strongly correlated to rainfall. But the danger can not be completely eliminated that a farmer will suffer a loss which is not covered enough (if at all) by the insurance benefits. This form of risk is generally referred to as basis risk (Miranda & Vedenov, 2001). The geographical basis risk can be minimised by a sufficient dense net of rainfall measurement points and the availability of contracts, wherein the farmer can spread out his risks based on several surrounding weather stations (Martin *et al.*, 2001; Turvey, 2001). Since rainfall in semi-arid regions is often very heterogeneously distributed, this dense net is necessary. It has to be mentioned that for these weather stations sufficient historical rainfall data are needed. Modern satellite imagery may help to monitor and assess soil moisture (Hazell, 1992).

3.2.3 Our question: Does the access to rain-index insurance change the management strategy?

The focus of the presented study is based on the following question: What influence does access to rain-index insurances have upon the management strategies of the farmers? Some studies exist which investigate the impact of index-based insurances on pesticide and nitrogen use: Horowitz & Lichtenberg (1993) demonstrate with the help of an analytical and a regression model that insured farmers are likely to undertake riskier production - with higher nitrogen and pesticide use - than uninsured farmers do. A similar result is pointed out in Mahul (2001), assuming a weather-based insurance. Wu (1999) estimates in an empirical study the impact of insurances on the crop mix and its negative results on soil erosion in Nebraska (USA).

As far as the authors are aware, no study has been carried out which investigates the effect of a rain index-based insurance on the chosen grazing strategy. In the present study we want to test the hypothesis that farmers who have closed an insurance contract choose less conservative grazing strategies than they would without the contract (Baumgärtner & Quaas, 2005; Quaas & Baumgärtner, 2005; Baumgärtner, 2006, forthcoming).

Why is an appropriate grazing strategy so crucial in semi-arid ecosystems? Degradation, i.e. the loss of productive land, is a major danger for these regions. A fifth of the world's drylands, or around a billion hectares, and an estimated 250 million people (UNCCD, 2004) are thought to be affected by human-induced soil erosion. The scientific debate goes on about the causes (Cowling, 2000; Briske *et al.*, 2003). Current research points out that grazing strategies have to be adapted to temporal and spatial heterogeneous forage production (Westoby *et al.*, 1989; Sullivan & Rohde, 2002). Furthermore, the role of rest periods for the pasture after droughts or in rainy years is emphasised to maintain the persistence and productivity of the rangeland system (see Chapter 2). In that study it was additionally shown that strategies which grant a rest period in rainy years act as a risk-reducing strategy for income. Hence, the supposed hypothesis can be specified: Access to rain-index insurances is supposed to lead to fewer rest periods in rainy years. The assumed reason is that with insurance the farmer can better cope with bad rainy years, and strategies which grant rests in rainy years and generate a reserve are no longer necessary to meet the selected target.

In Quaas *et al.* (2004) the role of the risk attitude of the farmer on the choice of the grazing strategy is investigated. The study reveals that the more risk-averse a farmer is the more sustainable is his grazing strategy independent of his time horizon. Hence, the hypothesis can be pointed out that risk management strategies (such as rain-index insurances) which reduce income risk lead to less conservative strategies.

3.2.4 Our approach

For the investigation we use an abstract ecological-economic model to compare the farmer's choice of a grazing strategy with and without insurance. Furthermore, it is aimed to investigate the impact of the resultant grazing strategy on the long-term productivity of the pasture. In this model the feedback dynamics between the ecological and economic system are included. The starting point of the analysis is an ecologically and economically successful farm in Namibia - the Gamis Farm. This is a Karakul sheep farm, which applies resting for a third of the pasture in years with sufficient rainfall. This case study is well studied from an ecological perspective (Stephan *et al.* (1998); see Chapter 2 of this thesis) and is taken as a starting point for the above mentioned ecological-economic study of Quaas *et al.*, 2004.

The decision criterion applied by the farmer is a safety-first rule (Roy, 1952; Telser, 1955; Kataoka, 1963): the primary goal being to reach a certain minimal income in each year. In developing countries the hazard of catastrophic losses is quite high (Hazell, 1992). Hence, the preferences of the farmer are mostly targeted towards assuring the livelihood for his family instead of maximizing the utility of income. For a more specific discussion of the appropriateness of this decision criterion we refer to the discussion section of the paper. In numerous case studies in the USA or developing countries agriculture economists have used the safety-first rule as a decision criterion. The fields of application range from soil conservation (Shively, 1997, 2000), fertiliser use (de Janvry, 1972; Van Kooten *et al.*, 1997), cropping systems (Adubi, 2000; Watkins *et al.*, 2004) to air pollution (Qiu *et al.*, 2001).

The present study is structured as follows: Initially important aspects of the case study are depicted and the ecological-economic model is presented. In a next step, the effects of grazing strategy and rainfall on income and biomass production over time are studied. Afterwards the impact of the decision criteria - safety-first rule - on the grazing strategy with and without access to rain-index insurances is investigated, as well as the consequences for pasture productivity. The impact of different ecological and climatic conditions is analysed subsequently. In the discussion section the acquired results are interpreted. Furthermore, the appropriateness of safety-first rules for decision making and of rain-index insurances as risk management measures is discussed.

3.3 Methods

3.3.1 Aim of the model

Our study aims to analyse how availability of index-based insurances change the grazing strategies of an individual farmer. We assume that he decides on the basis of a safety-first decision criteria. We analyse the role of farmer's preferences, time horizon and of ecological and climatic settings on the chosen strategy. Furthermore, we investigate the impact on the rangeland ecosystem.

3.3.2 Successful example: Gamis Farm in Namibia

The Gamis Farm is situated 250 km southwest of Windhoek in Namibia (24°05'S 16°30'E) in the district Maltahöhe close to the Naukluft mountains at an altitude of 1250 m. The climate of this arid region is characterised by low annual precipitation (177 mm/y) which is highly variable in space and time. The coefficient of variation is 56%. The vegetation type is classified by Giess (1998) as dwarf shrub savanna. Detailed information regarding the climatic, edaphic and botanical setting of the study site can be found in Maurer (1995).

Karakul sheep (race Swakara) are bred on an area of 30 000 hectares. The primary source of revenue is from the sale of lambskins. Additionally, the wool of the sheep is sold and meat is used for farm consumption (Tombrink, 1999). In good years, up to 3000 sheep are kept on the farm. For forty years, an adaptive management system has been tracking the variability in forage. During this time detailed records were kept by the owner, H.A. Breiting. The basis of the system is a rotational grazing system: The pasture land is divided into 98 paddocks; A paddock is grazed for a short period (about 14 days), after which it is rested for a minimum of two months. This system puts high pressure on the vegetation for a short time in order to prevent selective grazing. Moreover, the farmer has introduced an additional rest period: One third of the paddocks is given a rest during the growth period (September - May). Outside this period, all paddocks are grazed. In the literature this strategy is termed rotational resting (Heady, 1999; Quirk, 2002; Stuth & Maraschin, 2000) or rest rotation (Hanley, 1979). The Gamis Farm strategy is distinct from simple rotational resting systems in that

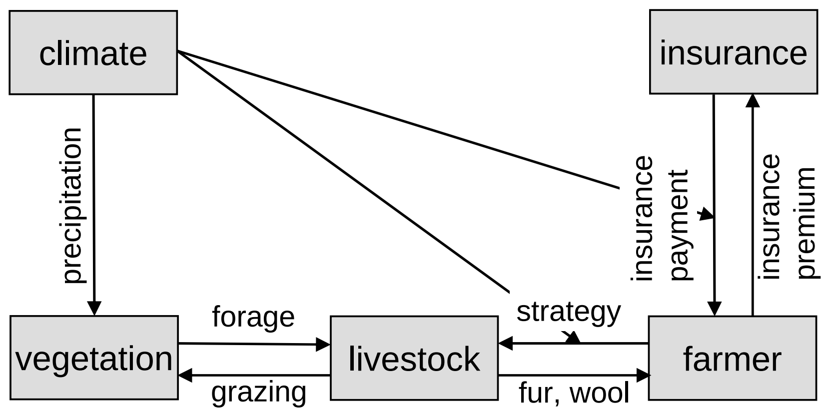

Figure 3.1: Causal diagram of the ecological-economic model

rest periods are granted only in years with sufficient precipitation. In years with insufficient rainfall this rest period is reduced or completely omitted. Further measures, such as renting of additional pasture, are taken during long periods of drought. Once a year at the end of the rainy season (April), the farmer decides how many of the lambs will be raised and whether additional land will be rented from farms elsewhere in the country (H.A. Breiting, pers. comm.). For a complete and detailed description of the grazing system see Stephan *et al.* (1996, 1998).

The grazing management system employed at the Gamis Farm has been successful over decades, both in ecological and economic terms. Therefore, it represents a model for commercial farming in semi-arid rangelands.

Currently, there is no rain-index insurance available in Namibia.

3.3.3 Structure

In this paragraph the main aspects of the ecological-economic model are presented (Figure 3.1): Four principal components drive the dynamics of the vegetation in a semi-arid savanna: (1) plant-available water, (2) plant-available nutrients, (3) fire and (4) grazing (Skarpe, 1992). Natural fires do not occur in this type of ecosystem (H.A. Breiting, pers. comm.). In savanna systems with low rainfall (below 200 to 300 mm), the vegetation is to a greater extent limited by water than nutrients (Le Houérou, 1989). Hence differences in plant-available nutrients resulting from different soil conditions were not explicitly simulated in the model. Accordingly, of the four components mentioned driving vegetation dynamics, only precipitation and grazing were explicitly included in the model.

The economic viability of alternative strategies was assessed from the number of livestock on the farm. The livestock constitutes the basis of the farmer's existence.

On the Gamis Farm, the farmer earns his living via revenue from the sale of lambskins and sheep wool. The number of livestock on the farm depends on the chosen management strategy; For example, if the farmer embarks on the strategy "resting in wet years", he determines whether some paddocks are rested, according to current rainfall. In addition, the livestock number is adjusted to the available forage. The surplus of livestock are slaughtered or sold. Hence, in this case, both vegetation and precipitation are key factors in determining the stocking rate. If an insurance contract is closed, the farmer receives an indemnity payment, when a weather trigger event falls short. In each year the farmer pays the insurance premium.

3.3.4 Submodels

Precipitation

Precipitation in arid regions is characterised by a low mean, but high spatial and temporal fluctuations. To simulate these properties the precipitation is modelled stochastically, following a log-normal distribution (Sandford, 1982). It is a right-skewed distribution: events with low rainfall are frequent, but single high-rainfall-events also occur. In the model only the proportion of rain available for the plants, indicated by p_t, was incorporated. The distribution is characterised by its mean $E(p)$ and its standard deviation $\sigma(p)$. The units of the measurement indicate the number of effective rain events per year (on Gamis Farm: events of more than 15 mm): For instance value 2 signifies 2 effective rain events. For easier handling a continuous scale is assumed.

Vegetation dynamics

For the vegetation dynamics a conceptual, highly abstract model with two relatively simple difference equations was used. The vegetation and sheep dynamics are described in detail in Chapter 2. The life history of the different vegetation types and their reaction to grazing and browsing is quite diverse (Noy-Meir, 1982). However, a single hypothetical perennial vegetation type was initially modelled. Two characteristics of the vegetation type were distinguished in order to illustrate that current biomass is not only dependent on current rainfall p_t but on grazing and rainfall history as well: The green biomass G_t describing the photosynthetic organs of the plant and being that part of the plants which serves as forage for the livestock; secondly the reserve biomass R_t (termed after Noy-Meir, 1982) describing the non-photosynthetic reserve organs below or above ground (cf. Figure 3.2). A fraction m of reserve biomass R_t is lost between the end of one growing season and the beginning of the next (maintenance respiration, mortality). The reserve

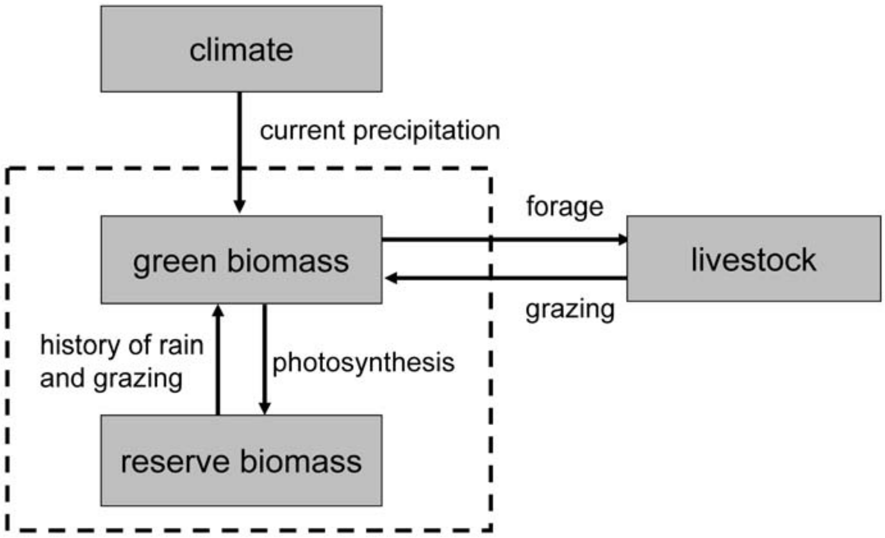

Figure 3.2: Causal diagram of the submodel vegetation dynamics

biomass R_{t+1} increases by photosynthesis in dependence on the amount of available green biomass G_t. For increment of reserve biomass R_{t+1} a distinction is made whether a paddock is grazed or rested. The extent to which new reserve biomass R_{t+1} is accumulated from green biomass G_t by photosynthesis is described in the growth rate of reserve biomass w_{res}. The impact of grazing is indicated by parameter c ($0 \leq c \leq 1$). c near 0 indicates low impact of grazing, c near 1 high impact of grazing. Rests occur because of planned rests or because of unplanned rests. Unplanned rests occur when livestock numbers are reduced due to mortality or sale in prolonged droughts and, hence, not all paddocks are used. The relationship leads to:

$$R^i_{t+1} = \begin{cases} R^i_t - m \cdot R^i_t \cdot (1 + d \cdot R^i_t) + w_{res} \cdot (1-c) \cdot G^i_t \cdot (1 - d \cdot R^i_t) \\ R^i_t - m \cdot R^i_t \cdot (1 + d \cdot R^i_t) + w_{res} \cdot G^i_t \cdot (1 - d \cdot R^i_t) \end{cases} \tag{3.1}$$

if paddock i is grazed/rested, respectively ($0 \leq c \leq 1$).

The equation holds for all time steps t, $t = 1, \ldots, T$, and for all paddocks i, $i = 1, \ldots, n$. T indicates the chosen time horizon in years and n the number of paddocks on the farm. A density dependence in reserve biomass growth is captured by the factors containing the parameter d. The higher d, the higher is the consumption and the lower is the growth.

The growth dynamics of the green biomass G_t^i of paddock i in time step t was defined by:

$$G_t^i = w_{gr} \cdot p_t \cdot R_t^i \qquad \text{for} \quad i = 1, \ldots, n \quad \text{and} \quad t = 1, \ldots, T, \tag{3.2}$$

with n denoting the number of paddocks and T the time horizon. The parameter w_{gr} is a conversion parameter, indicating the extent to which the green biomass G_t responds to reserve biomass R_t and current plant-available water p_t.

Livestock dynamics and grazing strategy

Without insurance, the annual income I_t of the farmer is equal to the number of livestock S_t on the farm since on the Gamis Farm, the farmer earns his living via the revenue from sale of lambskins and sheep wool.

Before first grazing in year $t = 0$, the farmer chooses a grazing strategy which is afterwards applied the whole time. He decides how much and when resting is granted for the pasture. We assumed as practised on the Gamis Farm that resting is carried out only in rainy years. Thus, the farmer's grazing strategy, indicated by $(\alpha, \hat{p})$, is characterised by two attributes:

- portion of the pasture rested α, varying from 0 to 100%.
- rain threshold $\hat{p}$, above which a part of the pasture is rested.

One unit of $\hat{p}$ corresponds to one effective rain event. The livestock number S_t grows exponentially with a given growth rate w_s. In case of purchases, livestock numbers are not restricted by the internal growth rate. In each year the current stocking rate S_t is limited by available forage G_t on pastures not rested. The surplus of livestock are slaughtered or sold. For detailed information regarding the ecological model I refer to Chapter 2.

Insurance

The rain-index insurance is realised as follows. As long as a prior specified annual rain level p^* (notice: p^* is independent of $\hat{p}$) is not reached, the farmer receives an indemnity payment i. On the other hand, he annually pays a premium b to the insurance. Thus the income of the farmer I_t in year t corresponds to the number of sheep S_t on the farm decreased by the premium b augmented by the payout i in years with bad rain:

$$I_t = \begin{cases} S_t - b + i & \text{if } p_t \leq p^* \\ S_t - b & \text{if } p_t > p^* \end{cases} \tag{3.3}$$

We assume an actuarially fair insurance. That means that the premium b the farmer has to pay each year is chosen to be equal to the expected payout of the insurance:

$$b = i \cdot P(p_t \leq p^*) \tag{3.4}$$

The insurance offers one specific insurance contract (i, p^*). At time $t = 0$ the farmer decides whether to close the insurance contract or not. This decision is retained for the whole time span.

Decision making - Safety-first rule

Background safety-first rule The decision criterion applied by the farmer is a safety-first rule: the primary goal being to reach a certain minimal income in each year. Purposefully, we do not follow the expected utility approach. In developing countries the hazards of catastrophic losses abound (Hazell, 1992). Hence, the preferences of the farmer are mostly targeted towards assuring the livelihood of his family instead of sole maximizing the utility of income. Three different safety-first criteria were developed by Roy (1952), Kataoka (1963) and Telser (1955) respectively. In this study the criterion introduced by Telser (1955) is applied: The decision maker determines firstly the set of strategies which lie in the accepted range of violation of a safety level. In the next step, from this set of admissible strategies, the one is chosen which generates the highest mean income. This leads to:

$$\max_{(\alpha,\hat{p})} E(I) \text{ subject to } P((I) \leq I_{min}) \leq P_{acc} \tag{3.5}$$

with $(\alpha, \hat{p})$ indicating the grazing strategy, I_{min} the safety level, P_{acc} the accepted probability of violation.

Consideration of time - A modified Telser' Safety-First Rule Telser's decision rule does not consider time. In our case we wanted to include the time horizon T of the farmer explicitly. Our modified version of Telser' Safety-First Rule includes time twice: Firstly, in the constraint for admissible strategies, secondly in the target function to maximize. That signifies we suppose the income of the farmer has to exceed a minimal income level $I_{min} = const$ in each year. Violations are allowed only with probability $P_{acc} = const$. From the set of the strategies which satisfy this condition the one is chosen which maximises the income flow over time $\sum_{t=1}^{T} I_t$. Discounting is not incorporated in the model, since we assumed that time preferences are included via the time horizon T. In order to compare the income flow for different time horizons T, the annual average income is considered. The expected value of this target variable is calculated over the probability distribution of the log-normal rainfall distribution.

Therefore, the farmer's decision problem is

$$\max_{(\alpha,\hat{p})} E(\frac{1}{T}\sum_{t=1}^{T} I_t) \text{ subject to } P((I_t) \leq I_{min}) \leq P_{acc}, \ \forall t = 1, \cdots, T \tag{3.6}$$

With access to insurance We assumed that the rain threshold p^* below which the insurance pays out is a fixed proportion of the long term mean of rainfall (cf. Turvey, 2001; Skees *et al.*, 2002). Firstly, the insurance company offers the following fixed insurance contract: $(i = 200, p^* = 0.75)$. This signifies that 200 units are paid out in case rainfall is below 75% of long term mean. For comparison: Turvey (2001) assumes a rain threshold of even $p^* = 0.95$ of long term mean. Skees *et al.* (2002, p.13) uses exemplarily $p^* = 0.67$ (corresponds to a strike of 200 mm rainfall with long term mean on 300 mm/y). One unit is equal to the value of one sheep. In this case, apart from the grazing strategy $(\alpha, \hat{p})$, the farmer decides whether he settles this specific insurance contract $(V = 1)$ or not $(V = 0)$. This decision is made once prior to first grazing and, afterwards, holds true for the whole time horizon. The farmer makes the decision of grazing strategy $(\alpha, \hat{p})$ and insurance V, likewise according to modified Telser' Safety-First Rule.

The decision problem is

$$\max_{(\alpha,\hat{p},V)} E(\frac{1}{T}\sum_{t=1}^{T} I_t) \quad \text{subject to } P((I_t) \leq I_{min}) \leq P_{acc}, \ \forall t = 1, \cdots, T \tag{3.7}$$

$$V \in \begin{cases} 1, & \text{closing of} \quad (i = 200, p^* = 0.75) \\ 0, & \text{not closing of} \quad (i = 200, p^* = 0.75) \end{cases}$$

under the given ecological dynamics and a fair insurance (cf. Equations 3.3, 3.4), with I_{min} minimal income, P_{acc} accepted level of violation of minimal income and T the time horizon of the farmer.

At a later stage we assume that the farmer can choose between nine different insurance contracts (i, p^*).

Simulation

The simulation runs in yearly time steps. First, 100 years of vegetation dynamics without grazing were run. This time span was used to minimize the influence of initial conditions of vegetation R_0 on the dynamics. A spatial implicit model is constructed: A farm with sixty paddocks of equal size and habitat conditions is assumed. The statistics were calculated over 5000 simulation runs, with rainfall drawn from the underlying probability distribution.

Scenario analysis and sensitivity analysis

One purpose of the present study consists in analysing the role of the farmers' preferences on the choice of the grazing strategy. For that reason, the three parameters reflecting the farmers' preferences (time horizon T, minimal income I_{min} and acceptance level of violation P_{acc}) were varied. The used parameter values can be found in Table 3.1. Similarly, the parameters which characterize the insurance (indemnity payment i, rain threshold p^*, below which insurance payment is granted) are indicated in Table 3.1. The table is completed to give an overview over the whole set of parameters. Income and indemnity payment are measured in sheep units. One unit insurance payout equals the value of one sheep. One unit green biomass corresponds to the forage needed for one sheep per year.

Another part of the analysis is the investigation regarding how robust the results are assuming different ecological and climatic conditions. Ecological conditions are represented, among others, by the vegetation growth parameters w_{gr}, the growth rate of the sheep w_s, impact of grazing c and initial condition of the vegetation R_0. Climatic conditions are reflected by the parameters of the precipitation distribution $(E(p), \sigma(p))$. In a sensitivity analysis these parameters were varied (according to Table 3.1) to detect their influence. With the help of latin hypercube sampling, 200 parameter sets are generated using the software SIMLAB 2.2 (Saltelli *et al.*, 2004). This method, by stratifying the input space into N desired strata, ensures that each input factor has all portions of its distribution represented by input values.

For each of the parameter sets, the corresponding values of the four following output variables have been calculated:

- expected annual average income $E(\frac{1}{T}\sum_{t=1}^{T} I_T)$ over time span T
- standard deviation of annual average income $\sigma(\frac{1}{T}\sum_{t=1}^{T} I_T)$ over time span T
- violation probability $P_{viol}(T) = P(I_T \leq I_{min})$ at time point T
- mean reserve biomass $E(R_T)$ at time point T

In a next step the Spearman's rank correlation coefficient was determined between these four output variables and the input parameters. This correlation coefficient is a measure of the correlation between data with monotone relationships.

Table 3.1: Parameter set used in the scenario analysis and in the sensitivity analysis (For the corresponding units it is referred to the explanations in the text)

	Parameters		Scenarios	Sensitivity analysis
Ecological conditions	Growth rate of green biomass	w_{gr}	1.2	0.5-2
	Growth rate of reserve biomass	w_{res}	0.2	-
	Strength of density dependence	d	0.000125	-
	Growth rate sheep	w_s	not limiting, since purchase assumed	0-1.5
	Impact of grazing	c	0.5	0-1
	Initial reserve biomass	R_0	4000	0-6000
Climatic conditions	Mean annual rainfall	$E(p)$	1.2	0-3
	Standard deviation of annual rainfall	$\sigma(p)$	0.7	0-1
Preferences of the farmer	Time horizon	T	10, 40, 70	-
	Minimal income	I_{min}	200, 500	-
	Acceptance level of violation	P_{acc}	0.02, 0.2	-
Farmers' choice				
Grazing strategy	Resting portion	α	0-1	0-1
	Rain threshold, above which a part of the pasture is rested	$\hat{p}$	0-4	0-4
Insurance	Indemnity payment	i	0, 200	0-350
	Rain threshold below which indemnity payment	p^*	$0.75 \cdot E(p)$	$(0.5 - 1) \cdot E(p)$

3.4 Results

3.4.1 Preliminary results

In order to understand the influence of insurance on farmer's choice of a grazing strategy, we conducted two prior steps: In the following paragraph the decision problem is left aside and the impact of the grazing strategies on expected annual average income and on expected annual average reserve biomass is shown. Furthermore the relationship between rainfall and income using a correlation analysis is presented. Thereby the case with and without insurance is contrasted. In the subsequent paragraph the role of the safety-first criterion without access to insurance on the chosen grazing strategy of the farmer is depicted.

Influence of grazing strategy and rainfall on income and reserve biomass

For the whole range of grazing strategies $(\alpha, \hat{p})$, the expected annual average income $E(\frac{1}{T}\sum_{t=1}^{T} I_t)$ over time horizon T (T=10, 40 and 70 years) was analysed (Figure 3.3a). The time horizon of the farmer is revealed of high influence on the superiority of the strategies $(\alpha, \hat{p})$ with respect to the expected annual average income $E(\frac{1}{T}\sum_{t=1}^{T} I_t)$: If T is short (T=10), the grazing strategies which involve few resting periods (low portion of rested pasture α and high rain threshold $\hat{p}$) have the highest expected annual average income (Figure 3.3a left). For T=40 the result is similar (Figure 3.3a middle). However, the expected annual average income decreases with increasing time horizon T under the assumed ecological set up. For very long time horizon T the qualitative behaviour changes strongly (Figure 3.3a right). Strategies with an intermediate level of resting generate the highest expected annual average income. The reason is that high livestock numbers are ensured in the long term only if reserve biomass production is promoted by partial resting.

The determination of the expected annual average reserve biomass over time span T ($T = 10, 40, 70$) for the whole set of strategies confirms the presumed result, that the higher the resting (either comparably higher portion α, or resting above a lower rain threshold $\hat{p}$) the higher the expected annual average reserve biomass $E(\frac{1}{T}\sum_{t=1}^{T} R_t)$ (Figure 3.3b). There exist different strategies which lead to the same level of reserve biomass: For strategy $(\alpha_1, \hat{p}_1)$ and a rested portion $\alpha_2 \leq \alpha_1$, there can be found a rain threshold $\hat{p_2}$ such that $(\alpha_1, \hat{p}_1)$ and $(\alpha_2, \hat{p}_2)$ have the same expected annual average reserve biomass over time T (i.e. iso-expected reserve biomass lines). For the rain threshold the corresponding holds. With increasing T the expected annual average reserve biomass decreases. Only with α higher than 0.7 does the expected annual average reserve biomass stay at a constant level in time.

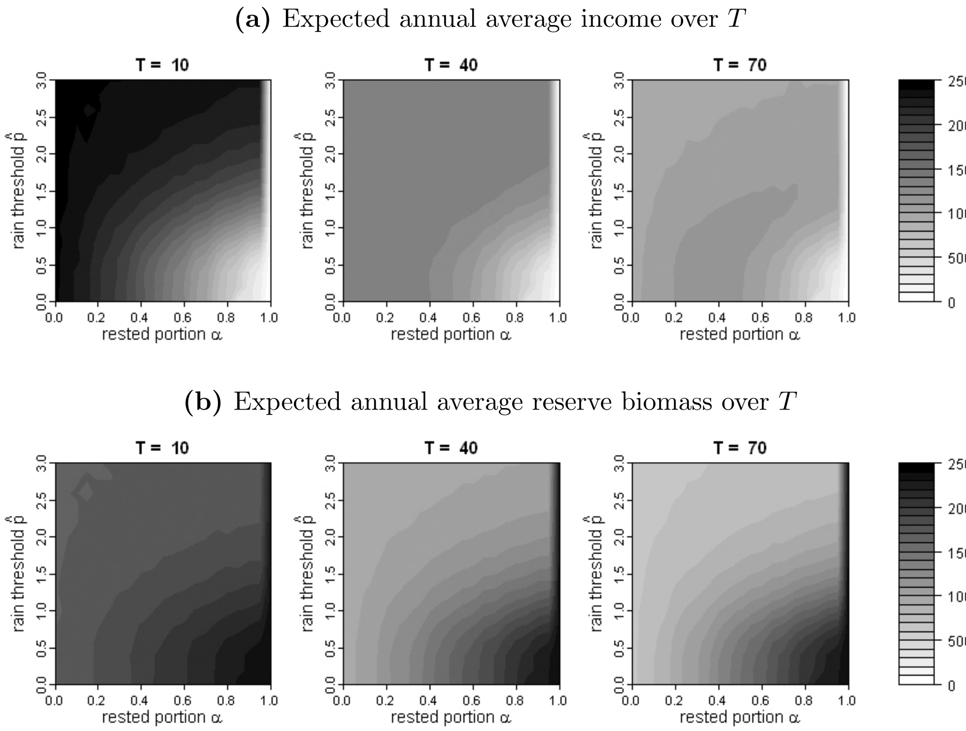

Figure 3.3: (a) Expected annual average income and (b) expected annual average reserve biomass over time horizon T and 5000 simulation runs for the whole set of grazing strategies. Farmers' time horizon T is varied $T = 10, 40, 70$.

Rainfall is a major driver of the system. Firstly it directly influences the amount of current green biomass and hence the current number of livestock on the farm, secondly it is stored as "rain history" in the reserve biomass, but, thirdly, it determines whether or not resting is carried out (if $p_t \leq \hat{p}$). Fourthly, in the cases involving insurance, rainfall determines whether an indemnity payment i of the insurance takes place or not.

The following correlation analysis was carried out, in order to understand to what degree the income I_t in year t depends on the current rainfall p_t. The role of the grazing strategy $(\alpha, \hat{p})$ and a settled insurance contract $(i = 200, p* = 0.75)$ was investigated thereby (Figure 3.4). One result remains independent of the grazing strategy: With insurance the impact of rainfall on income is lower than without insurance. This is not unexpected, since the purpose of rain-index insurance is to buffer the effect of rainfall on income.

Now the role of the grazing strategy is pointed out: Without any resting ($\alpha = 0$) and without insurance, there exists a strong influence of rainfall on income. However this influence diminishes with time. The history of grazing and rainfall

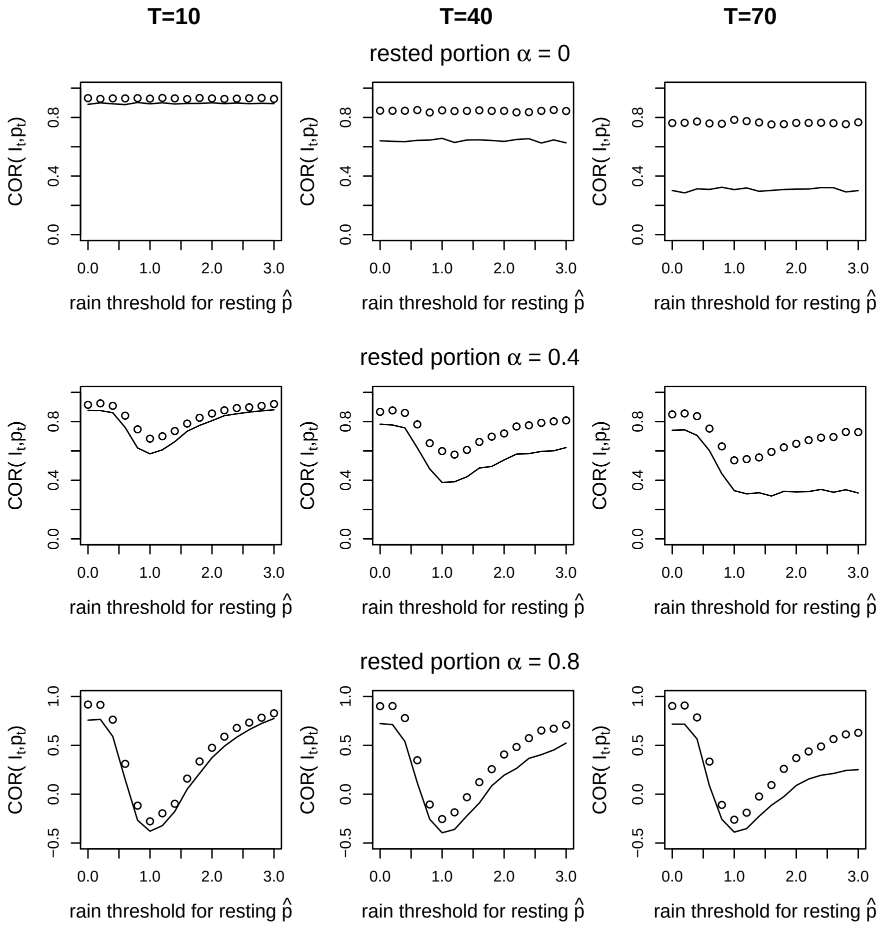

Figure 3.4: Spearman-correlation coefficient of income I_T and precipitation p_T at time $T = 10, 40, 70$, (1) without insurance (dots) and (2) with insurance ($i = 200, p^* = 0.75$) (line) for different grazing strategies $(\alpha, \hat{p})$.

stored in the reserve biomass becomes more and more important. The reduction of correlation in time is much stronger in the case with insurance. The reason is that the payout i and the prime b of the insurance remain constant in time, while the income gained from livestock is decreasing. Hence i and b have an increasing influence on income over time.

The higher the rested portion α, the more the threshold $\hat{p}$ influences the correlation between current rainfall p_t and income I_t: If resting is carried out in each year ($\hat{p}$ small) or almost never ($\hat{p}$ close to three) the correlation of I_t and p_t is high as in the cases before. That shows, although resting is carried out in each year ($\hat{p}$ small), income is highly depending on rainfall. However for intermediate thresholds the correlation of income and rainfall is even negative. It reaches its minimum at approximately $\hat{p} = 1$ (for comparison the median of the rainfall distribution lies at 0.85). For extreme α ($\alpha = 0.8$) the correlation is even negative. It results from the following aspect: If current rainfall p_t is above threshold $\hat{p}$, a high part of the pasture is rested. Therefore the number of sheep kept on the farm is very low and with it the income. This leads us to the conclusion that years with high rainfall are associated with a huge amount of resting and, hence, with low livestock numbers contrary to low rainfall years where no resting is carried out.

Concluding, the grazing strategy is of high influence on the correlation between income I_t and rainfall p_t at time t. However this influence does not qualitatively change with access to insurance.

What does safety-first criterion imply?

Three parameters characterize the preferences of the farmer: time horizon T, minimal income I_{min} and acceptance level of violation P_{acc}. First their influence on the optimal strategy assuming the safety-first criterion was investigated. For different levels of the preference parameters ($I_{min} = 200$, 500 and $P_{acc} = 0.02$, 0.2), the range of admissible strategies and the optimal strategy were calculated. If I_{min}= 0, the optimal strategy is the one which maximises the expected annual average income $E(\frac{1}{T}\sum_{t=1}^{T} I_t)$ (cf. Figure 3.3a), since all strategies are admissible. $I_{min} =$ 200 ($I_{min} = 500$) signifies that the farmer wants to ensure a minimal income level of 200 (500 respectively) sheep units per year. An acceptance level of $P_{acc} = 0.2$ signifies that he accepts a violation of minimal income in 20% of the cases, and a value of $P_{acc} = 0.02$ a violation rate of only 2%.

The influence of farmer's time horizon T (Figure 3.5) on his choice of grazing strategy was investigated:

Short time horizon: For a short time horizon T and comparably low minimal income $I_{min} = 200$, almost all strategies are admissible, independent of P_{acc}. The reason is that this low minimal income level seldom falls short, expect when applying strategies with an extremely high part of resting (Figure 3.5a right lower corner). The resulting optimal strategy ($\alpha = 0, \hat{p} = 2.8$) includes no resting.

Assuming high minimal income ($I_{min} = 500$) and very small acceptance of violation ($P_{acc} = 0.02$), strategies without any resting are not admissible (Figure 3.5d). The optimal strategy ($\alpha = 0.2, \hat{p} = 1$) includes a small part of resting. Hence, farmers with higher minimal income I_{min} rest more, ceteris paribus.

Long time horizon: For longer time horizons the range of admissible strategies decreases, assuming the preference parameters remain unchanged. If the minimal income is high ($I_{min} = 500$) and accepted violation probability very low ($P_{acc} =$ 0.02) , even no admissible strategy exists. Independently of farmer's preferences, only strategies including resting are admissible. Without resting the vegetation is

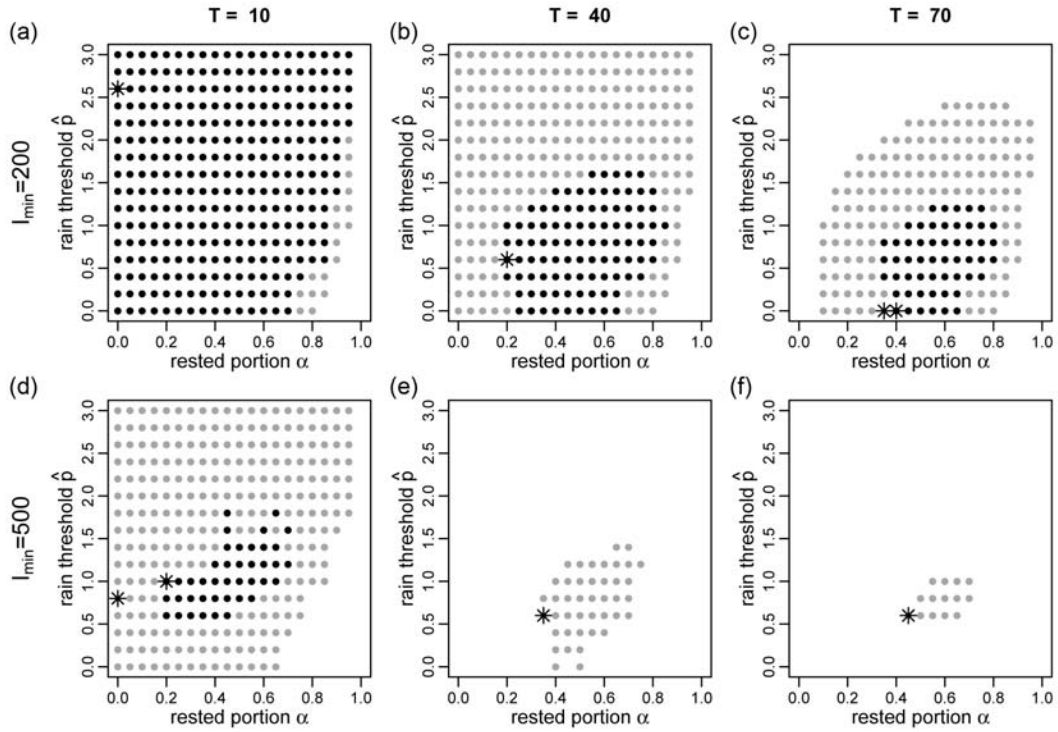

Figure 3.5: Admissible strategies without insurance for acceptance level of violation $P_{acc} = 0.02$ (black), 0.2 (grey) and the corresponding optimal strategies (*) applying the safety-first rule. The minimal income takes the values $I_{min} = 200$ (Figure a, b, c) and $I_{min} = 500$ (Figure d, e, f) and the time horizons are chosen to be $T = 10, 40, 70$.

in such bad condition that not enough livestock can be kept on the farm in order to ensure the minimal income I_{min}. Hence, for long-planning farmers, resting is an important part of the management strategy. But the frequency of resting depends on the preferences: For a farmer who seeks to reach a comparably high minimal income $I_{min} = 500$, resting is carried out not in each year (i.e. $\hat{p} = 0$), but only in rainy years ($\hat{p} > 0.6$) (Figure 3.5f). The reason is found in the following fact: In order to generate enough income in dry years, resting during these dry years is not possible.

3.4.2 Does insurance lead to a less conservative grazing strategy?

One specific insurance contract

In this paragraph we assume that the farmer decides, apart from the grazing strategy, whether he settles a specific insurance contract ($i = 200, p^* = 0.75$)

or not (decision problem Equation 3.7). If the farmer has settled the insurance contract, the insurance pays out 200 equivalent sheep units, whenever the rain p_t is lower than 75% of the annual mean rainfall $E(p)$. It should be noted once again here that the farmer makes the decision prior to $t = 0$ according to the safety-first rule and maintains the strategy and the insurance until the end of the time horizon.

According to his preferences, the decision maker determines the optimal grazing strategy in the case with insurance and the optimal strategy in the case without insurance. If the expected annual average income is significantly higher with, compared to without insurance, he settles the insurance contract and carries out the corresponding optimal grazing strategy $(\alpha, \hat{p})$.

Given a fixed grazing strategy, the insurance, assumed to be fair, does not change the expected annual average income. By affecting income deviations downwards, insurance may influence the range of admissible strategies. The analysis has shown that the range of admissible strategies extends with insurance. In other words, insurance leads to a higher economic window of opportunity. Only one exception exists that a strategy was admissible without, but not with insurance: Extremely high premiums in relation to income may involve shortfalls of the minimal income in wet years. However, this extreme case is unrealistic.

Consequently insurance can lead only to significantly higher expected annual average income and, hence, to another grazing strategy in one case: With insurance a strategy with significantly higher expected annual average income becomes newly admissible.

In Table 3.2 for different preference parameters it is contrasted whether insurance leads to distinct optimal strategies with significantly higher/lower expected annual average income or not. Only for two preferences, insurance leads to significantly higher expected annual average income over time span T: If the level of minimal income is high ($I_{min} = 500$) and time horizon T is short or middle. In order to facilitate better understanding regarding the reasons that insurance leads to distinct optimal grazing strategies under these preference parameters, some detailed considerations are necessary (cf. Figure 3.6, with $I_{min} = 500$):

Short time horizon: For a short time horizon ($T = 10$) and low accepted level of violation $P_{acc} = 0.02$, the settling of the insurance contract ($i = 200, p^* = 0.75$) leads to significantly higher income (cf. Table 3.2, 2200 versus 2400 units expected annual average income). In the case with insurance the optimal strategy implies no resting ($\alpha = 0$) compared to the case without insurance ($\alpha = 0.2, \hat{p} = 1$) (Figure 3.6a,d). Hence in this case, access to insurance leads to less resting.

The reason is that resting in rainy years is no longer necessary to ensure a certain level of livestock numbers and hence income in dry years, since the indemnity payment of the insurance is available during these years. The target to reach the

Table 3.2: Results of the Wilcox-Test to investigate whether insurance ($i = 200, p^* = 0.75$) leads to optimal strategies with significantly superior expected annual average income over time T compared to no insurance (P-level=0.05). Minimal income I_{min}, accepted violation level P_{acc} and time horizon T of the farmer are varied. "1*" denotes significant superiority with insurance,"0" no significant difference between with and without insurance, "-" no grazing strategy is admissible.

		$P_{acc} = 0.02$	$P_{acc} = 0.2$
$T = 10$	$I_{min} = 0$	0	0
	$I_{min} = 200$	0	0
	$I_{min} = 500$	1*	0
$T = 40$	$I_{min} = 0$	0	0
	$I_{min} = 200$	-	0
	$I_{min} = 500$	-	1*
$T = 70$	$I_{min} = 0$	0	0
	$I_{min} = 200$	-	0
	$I_{min} = 500$	-	0

minimal income $I_{min} = 500$ can be fulfilled. For medium time horizons ($T = 40$) the tendency is analogous: The insurance leads to significantly higher expected annual average income and less resting is optimal compared to the case without insurance.

Long time horizon ($T = 70$): As we have seen in Table 3.2, insurance does not lead to a significantly higher expected annual average income. The detailed analysis showed that only strategies with a medium level of resting are admissible (Figure 3.6f). Resting remains essential in the case with access to insurance too.

For an explanation let us look at an exemplary simulation run (Figure 3.7): For a strategy with no resting ($\alpha = 0, \hat{p} = 0.8$) the income flow in the case with (payout $i = 200$) and without insurance is mapped. The minimal income of the farmer I_{min} is assumed to be 500. The white bars indicate the years where rain does not reach the threshold $0.75 \cdot E(p)$ and hence the insurance pays out, if a contract is settled. Especially in these low rainfall years, the minimal income level I_{min} is violated without insurance (Figure 3.7b). However with insurance the level I_{min} is reached in the years where the insurance pays out, but not in all remaining years, when rainfall is above the rain threshold (for instance year 41; cf. Figure 3.7c). Two aspects play a role. Firstly the income in rainy years is reduced by the insurance premium. Secondly, the condition of the pasture becomes so bad

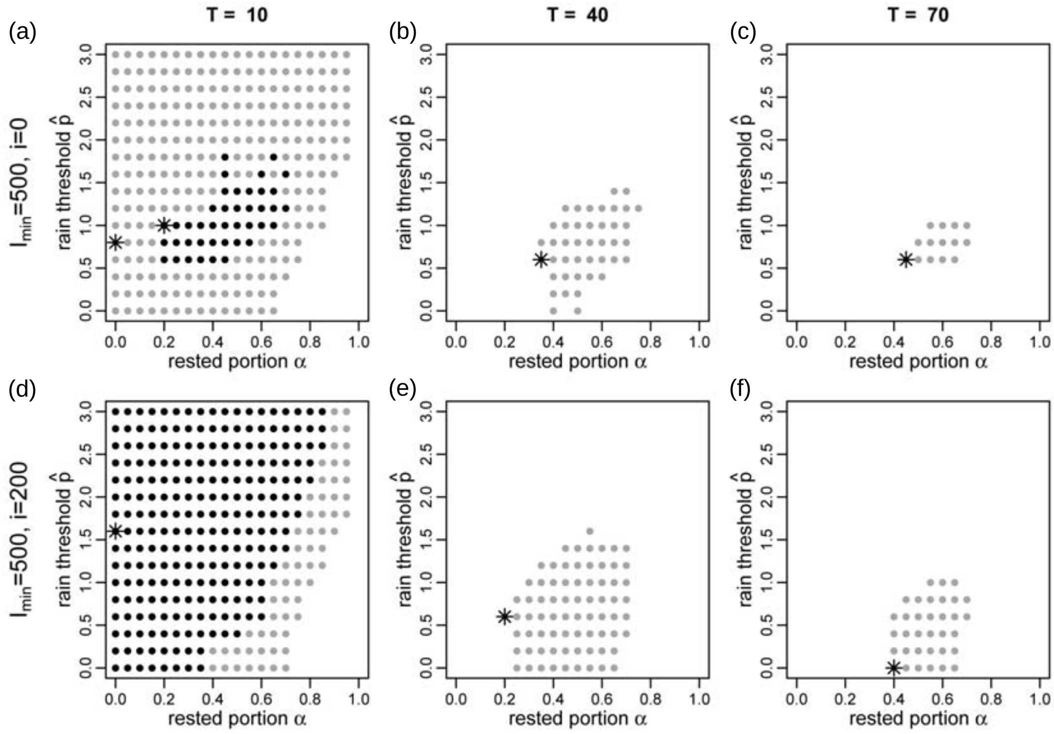

Figure 3.6: Admissible strategies for $I_{min} = 500$, acceptance level of violation $P_{acc} = 0.02$ (black), 0.2 (grey) and the corresponding optimal strategies (*) without insurance $i = 0$ (Figure a,b,c) and with insurance ($i = 200, p^* = 0.75$) (Figure d,e,f) and three different time horizons $T = 10, 40, 70$ applying the safety-first rule.

due to little resting, that even in years with sufficient rainfall the minimal income I_{min} is not reached. For comparison, a strategy with a high portion of resting ($\alpha = 0.4, \hat{p} = 1.5$) is mapped, assuming the same rainfall scenario (Figure 3.7d). Applying this strategy, where resting in rainy years is granted, no insurance is necessary to reach $I_{min} = 500$ with an accepted violation probability of $P_{acc} = 0.2$. Summarizing, resting is important to reach I_{min} independent of the insurance payout, if the farmer has a long time horizon.

Getting back to the expected annual average income for time horizon $T = 70$ (Figure 3.6c,f): Surprisingly, with insurance the range of admissible strategies is increased by strategies which rest even more - not only in rainy years but in each year ($\hat{p} = 0$). The reason is the following: Without insurance the farmer has to care for sufficient livestock on the farm in dry years. Hence in dry years resting is not possible in order to reach the minimal income. With insurance the income is supported in dry years by the insurance payment. Hence "resting in each year" becomes admissible.

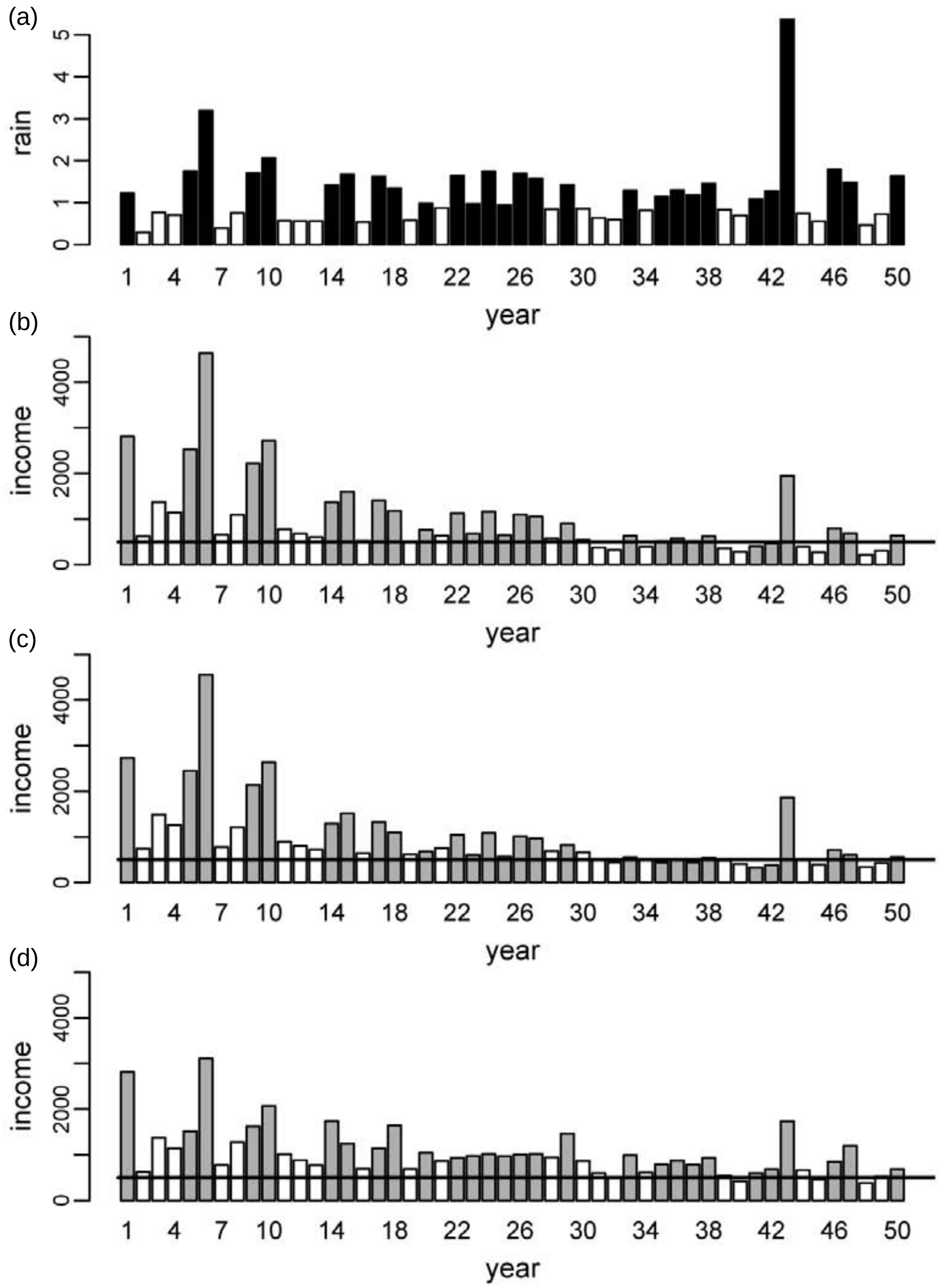

Figure 3.7: a) Rainfall, b) Income applying strategy ($\alpha = 0, \hat{p} = 1.5$) without insurance, c) Income applying strategy ($\alpha = 0, \hat{p} = 1.5$) with insurance (payout $i = 200$), d) Income applying strategy ($\alpha = 0.4, \hat{p} = 1.5$) without insurance, for a period of 50 years (α - rested portion, $\hat{p}$ - rain threshold above which resting is carried out).

Choice between different insurance contracts

Until now we supposed that the farmer has only the choice of deciding whether he settles the specified insurance contract or not (indemnity payment $i = 200$, rain threshold $p^* = 0.75$ below which payment). In the following it is depicted whether the results change, if the farmer can choose between nine different insurance contracts. The contracts result from all possible combinations of rain threshold p^* and indemnity payment i:

- rain threshold above which payout $p^* = 0.55, 0.75, 0.95$
- indemnity payment $i = 100, 200, 300$ sheep units

From all insurance contracts that contract was chosen, which involves an admissible grazing strategy with the highest expected annual average income.

Similar to the analysis above (Table 3.2), it was tested whether for this contract and the associated grazing strategy the expected annual average income was significantly higher compared to without any insurance. The analysis was carried out for the same preference sets and time horizons as in Table 3.2.

The results depicted the same optimal strategies as in the case where only the insurance contract ($i = 200, p^* = 0.75$) was available: Insurance leads to significantly higher expected annual average income over time horizon T for exactly the same preferences parameters: If the level of minimal income is high ($I_{min} = 500$) and the time horizon is short or middle.

The optimal insurance contract for the first case ($T = 10, I_{min} = 500, P_{acc} = 0.02$) is a payout of $i = 200$ when rainfall is 55% of the long-term rainfall mean ($p^* = 0.55$). For the second case ($T = 40, I_{min} = 500, P_{acc} = 0.2$), the optimal contract is, as before, ($i = 200, p^* = 0.75$).

Consequently the availability of different insurance contracts does not change the previously found results. These indicated that only for short or middle time horizons and high risk aversion insurance leads to significantly higher income than without insurance. The associated grazing strategies imply less resting. Risk aversion is defined here in the following sense: Farmer 1 is "more risk averse" than farmer 2, if he has higher minimal income level assuming the same accepted violation probability (i.e. $I^1_{min} > I^2_{min}$ and $P^1_{acc} = P^2_{acc}$) or if he accepts only a lower violation probability assuming the same minimal income (i.e. $P^1_{acc} < P^2_{acc}$ and $I^1_{min} = I^2_{min}$).

How robust are the results for different ecological and climatic settings?

Table 3.3: Spearman Rank Correlation Coefficient for four target variables and six ecological and climatic parameters, time horizon chosen is 70 years, significance level * P=0.05, *** P=0.001

	$E(\frac{1}{T}\sum_{t=1}^{T} I_t)$	$\sigma(\frac{1}{T}\sum_{t=1}^{T} I_t)$	$P_{viol}(T)$	$E(R_T)$
w_{gr}	0.367***	0.349***	-0.324***	0.289***
w_s	0.093	0.13	-0.157*	-0.034
$E(p)$	0.751***	0.377***	-0.600***	0.745***
$\sigma(p)$	-0.037	0.337***	0.016	0.038
c	0.064	0.122	0.155*	-0.170*
R_0	0.092	0.065	-0.096	0.077

The Spearman Rank Correlation Coefficient indicates a highly significant positive impact of mean annual precipitation $E(p)$ and growth rate of green biomass w_{gr} on expected annual average income $E(\frac{1}{T}\sum_{t=1}^{T} I_t)$ over time span T and mean reserve biomass $E(R_T)$ at time point T (Table 3.3). These parameters are, in addition, significantly negatively correlated to the probability $P_{viol}(T)$ with which the safety level I_{min} is violated. The parameter indicating the impact of grazing c is significantly correlated to mean reserve biomass $E(R_T)$ as well as to expected annual average income $E(\frac{1}{T}\sum_{t=1}^{T} I_t)$. Here, only the results for time horizon $T = 70$ years are presented. An analysis not indicated here reveals that, qualitatively, the same holds for other time horizons.

The previous results - access to insurances leads to ecologically detrimental grazing strategies assuming a short term thinking farmer - do not hold if the regeneration rate of the vegetation is high (high mean annual precipitation $E(p)$ or high growth rate of green biomass w_{gr}). Since in Chapter 2 it was shown that, assuming regeneration rate of the vegetation to be high enough, resting is not necessary to maintain the pasture in a good condition. Hence, in this case access to insurance does not negatively influence the vegetation. However, semi-arid regions are just characterised by low mean annual precipitation $E(p)$ and low growth rate of green biomass w_{gr}.

Different initial conditions (indicated by R_0) have a small effect on the results, apart from the case where the vegetation condition is so bad that stock farming is not possible. The standard deviation of rainfall $\sigma(p)$ influences significantly the standard deviation $\sigma(\frac{1}{T}\sum_{t=1}^{T} I_t)$ but not the expected annual average income $E(\frac{1}{T}\sum_{t=1}^{T} I_t)$.

3.5 Discussion

Before we discuss the main topic of this study - the influence of access to insurances on the grazing strategy - let us first look at the assumed decision criterion of the farmer, the safety-first rule.

3.5.1 Appropriateness of safety-first rule as decision criterion

The decision criterion applied is a safety-first rule: the primary goal being to reach a certain minimal income in each year. The present study assumes its appropriateness for decision making in certain circumstances: Firstly, if hazard of high income loss exists (e.g. in the case that drought is prevalent) and secondly, when the farmers' actions are targeted towards reaching a certain income level, such as for instance coverage of the livelihood of their families. Consequently, especially for subsistence farmers in developing countries this criterion seems to be a more adequate description of decision making than pure expected utility maximization of income. Numerous studies in agricultural economics in which the criteria is used support this (including Shively, 1997, 2000; Van Kooten *et al.*, 1997; Qiu *et al.*, 2001). This decision criterion stands for ensuring economic viability of the managed system.

From the theoretical point of view, this criterion is investigated in the economic literature too. In contrast to the mean-variance approach, which penalises upper deviation from the mean (so called potentials) in the same manner as downside deviation (Grootveld & Hallerbach, 1999), the safety-first criterion is a downside risk measure. Only deviations downwards from the mean are penalised (Berck & Hihn, 1982; for a discussion of variance versus downside risk cf. Grootveld & Hallerbach, 1999). Under certain assumptions, a correspondence between the safety-first criterion and the Expected Utility Model can be stated (cf. Pyle & Turnovsky, 1970; Levy & Sarnat, 1972; Bigman, 1996).

3.5.2 How do farmers' preferences influence the grazing strategy?

In this paragraph this question is analysed assuming no access to insurance. Our results show that the strategy the farmer chooses applying the safety-first rule is highly dependent on his time preferences.

Decisions of farmers who consider just a short time horizon include resting at all only when the farmers are highly risk-averse (high minimal income and at the same time low accepted violation probability). They need to rest in rainy years in order to generate forage reserves for the livestock in dry years. Contrarily speaking, low risk-averse farmers do not rest. The reason: Since risk and the long term impact of grazing on the pasture do not matter, they apply a strategy wherein the pasture is fully stocked with livestock, and thus the highest expected annual average income is generated.

A long-term-thinking farmer acknowledges that resting a part of the pasture is fundamental, since a good long-term condition of the pasture is crucial for maintaining productivity and hence sufficient income. This evaluation is independent of his attitude towards risk. It should be mentioned once again here that, his attitude towards risk is characterized in the present study by the level of minimal income needed and by the accepted probability with which the minimal income level may be violated. However, the risk attitude of the farmer has an effect thereon, in which years rest periods are granted. If the farmer is risk avers (high minimal income and low acceptance to violate this target), resting is not carried out in each year, but only in years with sufficient precipitation. Otherwise, if resting would be carried out also in dry years, the livestock numbers need to be reduced during these years for two reasons: because of the lack of rain and because of the granting of rests for a part of the pasture. Consequently, the minimal income level cannot be reached. Contrarily, less risk-averse farmers do not have to be cautious for the choice of the year to rest. This result holds independent of the time horizon.

Discounting is not explicitly included in the model, however the results are assumed to hold, since discounting acts in the same direction as a shorter time horizon.

3.5.3 Influence of rain-index insurance on choice of grazing strategy

The principal focus of the present study was to investigate whether the settling of a rain-index-based insurance contract influences a farmer's strategy choice towards less conservative strategies. As far as the authors are aware, no study has been carried out which has investigated the effects of a rain index-based insurance on the chosen grazing strategy. Assuming the simple version presented here of a fair insurance contract without costs, this previously stated hypothesis can be confirmed: Insurance leads to less conservative strategies - but only for farmers with short time horizons. Risk-averse farmers with short time horizons can cope with dry years by using the indemnity payment of the insurance. Hence, resting during the other rainy years in order to generate forage reserves is not necessary, when compared to the case without insurance. Less risk-averse and short-term-thinking farmers apply, independent of the insurance, no strategy in which rests for the pasture are included. However, the hypothesis proves to be false when a long term thinking farmer is assumed. Resting in rainy years is indispensable with or without insurance and independent from farmer's attitude towards risk - under the underlying ecological conditions. The reason is that the indemnity payment helps to cope with income shortfalls in dry years. But in the remaining years, where rainfall is higher, enough livestock can only be kept on the farm when the productivity of the pasture is high over the long term too. To ensure this, resting in rainy years is needed in order to retain the condition of the pasture at a high level.

Unexpectedly, assuming a farmer with long time horizon, insurance leads to even more resting: Not only in rainy years, but now in dry years as well. It results from the following effect: In dry years the minimal income level is reached despite resting a part of the pasture, since the indemnity payment is available for the farmer. The ecological study of the system has shown that prior resting in rainy years is important for pasture regeneration (see Chapter 2). However, to rest all of the time would obviously improve the pasture condition even more. Since the pasture condition is crucial to ensure income over the long-term, to rest a part of the pasture in each year is an appropriate strategy for the farmer.

3.5.4 Resting in rainy years has two functions

The grazing strategy to rest in rainy years fulfils two functions:

1. smoothing of income
2. investment in income for the future.

Let us look at these two functions more in detail: The first point - reduction of the income variability - follows since resting in highly productive years generates a forage reserve for dry years. Hence it acts as ex ante risk reducing strategy. The second point - the investment in the income for the future - results since resting ensures high pasture productivity in the future. Summarizing, this strategy invests into an ecological buffer which helps to reduce risk (Baumgärtner & Quaas, 2005; Quaas & Baumgärtner, 2005; Baumgärtner, 2006, forthcoming). The term risk applied here means the two aspects: reduction of income variability and of decreasing productivity with time.

However, the economic buffer mechanism - the insurance - can take over only the first function, but not the second function. This explains why for long-term thinking farmers both aspects may play a role: Resting to invest in the future and maintain the pasture in a good condition and index-based rain insurance to overcome catastrophic droughts when biomass reserves generated by resting are not sufficient.

One consequence of the present study is the following: The incentives for farmers to change their strategies under insurance availability has to be kept in mind, if policy instruments for reducing income risk, such as insurance, are going to be designed. For this issue a fundamental understanding of the impact of governmental policies offering risk management strategies on land use is necessary (Wu, 1999). Ecological-economic simulation models which explicitly include the relevant ecological and economic aspects and feedback dynamics, such as the study presented here does, may offer an adequate approach.

The question arises, how insurance contracts have to be designed so that short-term thinking farmers do not choose less conservative strategies. It can not be answered here. Only one aspect may be pointed out: The self-insurance of the farmers by appropriated land use strategies needs to be encouraged (for instance through education). This results also from the study of Sakurai & Reardon (1997) who state that farmers who are self-insured in their region demand less formal drought insurance. For circumstances where self insurance is not sufficient (see also Gautam *et al.*, 1994), the availability of index-based insurances is an important alternative.

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3.7 Link to the proceeding chapter

Chapter 2 and 3 considered the commercial Gamis Karakul sheep farm (Namibia) as a foundation to a broader investigation of the relevance of resting during wet years for maintaining pasture productivity and reducing income risk over time.

Chapter 3 was dedicated to explore the interplay of ecological and economic risk management strategies. Using an ecological-economic model, the question was adressed, whether risk reducing strategies, such as resting during wet years, are maintained under aspects of global change. Exemplarily the access to rain-index insurances was considered. The preferences of the farmer were identified as highly influential, whether resting during wet years is maintained under these changed economic conditions as well.

In the following chapter, the value of resting in a second, different range management system in Namibia is investigated. The pastoral-nomadic Ova-Himba people in northern Namibia applied, until very recently, a sophisticated management system which combined seasonal resting and the maintenance of reserves for times of drought. I present a second ecological model, specific to the ecological conditions and management system of the Ova-Himba. The traditional strategy will be compared to alternative strategies, where seasonal resting and/or granting of reserves for drought are no longer used. It is aimed to analyse whether resting is a key factor for this management system. Furthermore the consequences of changing economic conditions, such as access to purchase markets, will be investigated. Based on the results of the two case studies, I discuss the role of resting in sustainable adaptive management systems in general (Chapter 5 - Synthesis).

4 Learning from indigenous knowledge: modelling the pastoral-nomadic range management of the Ova-Himba[1]

4.1 Abstract

It is widely accepted that successful grazing management strategies in semi-arid ecosystems need to be adapted to the highly temporally and spatially heterogeneous forage production. Nevertheless, a full understanding of the key factors and processes for sustainable adaptive management has yet to be reached. The investigation of existing, successful range management systems by simulation models may help to derive general understanding and basic principles.

The semi-nomadic Ova-Himba in northern Namibia applied a sophisticated management system until the mid-nineties of the last century which combined season-dependent pasture use (resulting in rainy season pastures and dry season pastures), preservation of reserves for drought and sanctions for rule breaking. A stochastic ecological simulation model is constructed which represents the main aspects of this management system. With this model we analyse (i) which components of the traditional Ova-Himba strategy are essential for sustainability and (ii) what happens to the state of the rangeland system under socio-economic changes.

The study shows that temporally and spatially heterogeneous pasture use yields higher productivity and quality of a pasture area than a homogeneous, permanent grazing pressure. Two aspects are of importance: (a) intra-annual heterogeneous use: resting of the dry season pastures during the rainy season and (b) inter-annual heterogeneous use: spatial extension of grazing in years of drought. This management system leads to an effective build up and use of a buffer in the system - the reserve biomass (the non-photosynthetic reserve organs of the plants), an indicator for grazing and management history.

[1] A slightly modified version of this chapter is previewed for submission to a journal with focus on applied ecology: B. Müller, B., Linstädter, A., Frank, K., Bollig, M., Wissel, C.: Learning from indigenous knowledge: modelling the pastoral-nomadic range management of the Ova-Himba.

Analysing exemplary purchases as one form of socio-economic change, we demonstrate that relieved market access to purchase livestock may lead to a decline in vegetation quality. However, cattle production increases as long as rest periods on parts of the pasture during the rainy season are granted.

Methodologically, we emphasise that simulation models offer an excellent framework for analysing and depicting basic principles in sustainable range management derived from indigenous knowledge. They afford the opportunity to test whether these basic principles are also valid under different ecological and socio-economic settings.

4.2 Introduction

The livelihood of a vast majority of people in (semi-) arid regions depends on livestock farming. Hence, an existential problem of land use in these regions is the loss of productive land.

The mechanisms of land degradation are still being controversially discussed: An equilibrium view dominated until the beginning of the nineties of the last century. In that perspective it was assumed that rangeland systems reach an equilibrium state primarily determined by biotic factors, with grazing being the main driving force for vegetation change (Lamprey, 1983; Dean and MacDonald, 1994). Since the mid-nineties, highly variable and unpredictable rainfall was seen to be the major driving force at least in "arid" rangelands with rainfall variability higher than 30%. Thus variability in abiotic conditions would be the key determinant, and biotic factors such as grazing pressure would have only marginal influence on vegetation dynamics (Westoby et al., 1989; Behnke Jr et al., 1993; Scoones, 1994; Sandford, 1994).

This non-equilibrium concept has been vividly discussed by ecologists in the past years (Cowling, 2000). One of its main tenets, i.e. that herbivores have minimal impact on vegetation or production, was questioned (Sander et al., 1998; Illius and O'Connor, 1999). It is argued that strong equilibrial forces may act over a limited part of the system. For example, "key resources" such as dry-season ranges, where water is also available during dry seasons, enables heavier use of wet-season ranges. As a consequence, animal numbers and available fodder on wet-season ranges may become uncoupled, especially during droughts. Most promising appear to us recent attempts which consider both, biotic and abiotic factors to be essential for vegetation dynamics on different temporal and spatial scales (Illius and O'Connor, 1999, 2000; Fuhlendorf and Engle, 2001; Briske et al., 2003; Vetter, 2005). However, a full understanding of the underlying key aspects and processes for sustainable range management is not reached yet and hence the debate goes on (cf. Fynn and O'Connor, 2000; Sullivan and Rohde, 2002).

These shortcomings can be overcome by analysing successful range management systems in semi-arid ecosystems. For instance, pastoral nomads in different parts of the world have developed sophisticated strategies adapted to the temporal and spatial heterogeneity of fodder production (Galaty and Johnson, 1990; Fratkin, 1997; Bollig and Schulte, 1999; Niamir-Fuller, 2000). Only a few studies emphasise the value of analysing this indigenous knowledge with respect to range management (e.g. Fernandez-Gimenez, 2000; Griffin, 2002). It consists of biophysical observations, skills, technologies as well as norms and institutions (Fernandez-Gimenez, 2000). The transfer from indigenous knowledge to scientific knowledge may help to find out basic principles. These principles could be, under certain conditions, applicable to other range management systems with different ecological and economic settings.

In this study the range management system of a Ova-Himba community in Namibia is taken as the starting point for the analysis of a "good practise" example. Up to the mid-nineties the Ova-Himba herders had maintained a successful land use system. It was based on joint management of the communal goods "pasture" and "water" and included a season-dependent pasture use and the preservation of reserves for drought. Rule breaking was sanctioned within a community (Bollig, 1997; Schulte, 2002a). Before Namibia's independence in 1990 they were subsistence herders since livestock trade was prohibited under colonial rule (Bollig, 1998). As with most of the transhumant management systems in general (Niamir-Fuller and Turner, 1999) the political and socio-economic circumstances for the Ova-Himba people are changing recently: Their management system is affected by numerous changes due to internal and external factors which interact with each other (population and livestock growth, increasing installation of boreholes, installation of infrastructure permitting sale and purchase, changing institutions). Today, it is crucial to understand (i) which components of the traditional management system of the Ova-Himba are essential for sustainable land use, and (ii) what happens to the state of the rangeland system under socio-economic changes. Concerning the second question, we focus here on the economic and ecological consequences of a relieved market access to purchase livestock. To answer these questions, a thorough understanding of the dynamics and of the crucial features of a successful land management system is needed, and a transfer of these features to other range management systems should render meaningful results.

A promising approach to tackle these questions offers simulation models. They are most often the only possibility to investigate the long-term dynamics of range management systems in arid ecosystems, since its impact becomes visible only after decades (Wissel et al., 1996; Jeltsch et al., 2001). In numerous studies the spatial and temporal heterogeneous response of vegetation dynamics to grazing and precipitation is investigated by the help of modelling (Pickup, 1996; Wiegand and Milton, 1996; Jeltsch et al., 1997; Illius et al., 1998; Janssen et al., 2000;

Weber et al., 2000; Adler et al., 2001; van de Koppel et al., 2002; Pütz, 2005, and Chapter 2 of this thesis). However the few modelling studies of mobile management systems of pastoral nomads are mostly focused on socio-economic issues (Rouchier et al., 2001; Kuper et al., 2003; Thornton et al., 2003) and not on the impact on vegetation (as exception Coughenour, 1992; Illius and O'Connor, 2000).

In the current study a spatially implicit ecological model is used to investigate the range management system of one settlement of Ova-Himba herders including its pastures. The long-term impact of the grazing regime under stochastic rainfall on the two primary sources of fodder - annual and perennial grasses is investigated.

We will give an introduction to the ecosystem and management system of the Ova-Himba. Secondly we present the spatially implicit model with its model rules. We analyse the consequences of the traditional strategy on vegetation and livestock dynamics over the long term. Then the traditional strategy is compared (i) to alternative strategies where parts of the traditional one are altered, and (ii) to strategies including purchase of livestock. Using global sensitivity analysis we investigate whether the results found hold true for different ecological and economic conditions.

4.3 Methods

4.3.1 Study area

The Kaokoland (now part of Kunene Region) is situated in the north-western part of Namibia and covers an area of about 50 000 km^2. Mean annual precipitation ranges between 50 mm/y in the far west and 380 mm/y in the east. The study site in northern Kunene Region (around Omuramba North) receives about 280 mm/y and has a rainfall variability higher than 30% (Schulte, 2002b). The rainy season starts in November/December and lasts until March/April (Sander and Becker, 2002). The geomorphology of this landscape is quite heterogeneous due to small-scale differences in topography and geology. The vegetation can be characterized as savanna woodland or, more precisely, as Mopane savanna (cf. Giess, 1998). This vegetation type has a closed herbaceous layer and an open woody layer with cover values between 2 and 15%, dominated by the species *Colophospermum mopane* (Schulte, 2002b) (Figure 4.1). The colonial encapsulation (Bollig, 1997) until 1990 forced the Ova-Himba to subsistence living without permission for trading livestock.

Since probably the 18th century, the land has been grazed by large herds of domestic livestock (Bollig and Vogelsang, 2002), while evidence of early pastoral-foraging dates back some 2000 years (Vogelsang, 2002). Until now semi-nomadic herders of the people Ova-Himba earn their living by keeping cattle and small-stock (Figure 4.2).

Figure 4.1: Rainy season pastures (foreground) and dry season pastures (background; behind the rocky outcrop) during a rainy season with average rainfall around Omuramba settlement in north-eastern Kaokoland (Namibia). Photo taken by Anja Linstädter 15.03.1996.

Figure 4.2: A Himba herdsman of the Omuramba settlement area in a cattle kraal, the inner part of a household. Photo taken by Anja Linstädter 02.05.1997.

The Ova-Himba people always applied a mobile management system adapted to highly unpredictable rainfall and patchy resource distribution. However, due to internal and external forces their grazing regimes seem to always have a limited lifespan. So the strategy described in the following was applied from the sixties to the mid-nineties of the last century. The grazing regime comprised a season-dependent use of the pasture. During the rainy season the pastures (RSP) around the households (onganda) were grazed. These areas were often characterized by deep soils since households are situated near ephemeral rivers (Figure 4.3). During the dry season, only lactating animals were kept in the neighbourhood. The main part of the flock was moved to cattle camps situated in dry season pastures (DSP) in a distance of at least 2 km to the households. These areas were characterized by permanent water sources such as boreholes, in comparison to temporal water sources in the rainy season pastures (Behnke Jr, 1999). Because the dry season pastures were situated further away from the ephemeral rivers, they were mainly characterized by shallow soils (Sander and Becker, 2002; Schulte, 2002b). During the rainy season, these areas were not allowed to be grazed by livestock. At the onset of the dry season, herdsmen from different households made arrangements in order to move to neighbouring cattle camps at the same time. In this fashion negative impact from trampling could be minimized. For years of very low rainfall and fodder production, reserves for drought (RFD) were held back. These areas were difficult to access and/or had a greater distance to the water sources. Only under emergency conditions in times of drought, herdsmen were allowed to use these pastures. For a more detailed description of this complex management system we refer to Bollig (2002) and Behnke Jr (1999).

The deep soils on rainy season pastures maintained a higher productivity than the shallow soils on dry season pastures or on reserves for drought (cf. Schulte, 2002a). Due to the heavy impact of grazing throughout the year, rainy season pastures were dominated exclusively by annual grasses and herbs (of partly low grazing value). Dry season pastures were mainly covered by annual grasses such as for instance *Schmidtia kalahariensis*. The resting of these areas during the rainy season avoided early disturbance during their growing time. Here, intensive grazing has changed natural species composition and abundance. A dominance of perennial grasses without livestock grazing, mainly *Stipagrostis uniplumis*, was proven by grazing exclosures on both rainy and dry season pastures (Schulte, 2002b). Today perennial grasses have cover values generally lower than five percent (ibid.). In contrast, on reserves for drought the human impact was less detectable. The proportion of perennial grasses was higher, unless it is inhibited by a soil which is too shallow. This described strategy we will call in the following "Traditional strategy". Bush encroachment in the heavily used pastures did not take place, since shrub and tree density was limited by woodcutting and browsing.

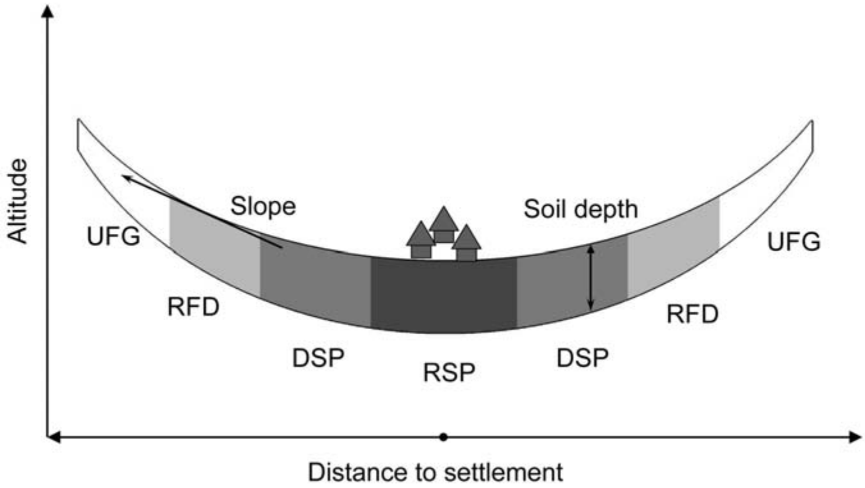

Figure 4.3: Schematic characterization of pasture types in northern Kunene Region: Distance to settlement, altitude, slope and soil depth of pasture types RSP (rainy season pasture), DSP (dry season pasture), RFD (reserves for drought) and UFG (area unsuitable for grazing). The hue indicates the intensity of pasture use (dark: heavy use, white: no use). Note that this sketch does not give accurate, to-scale values for any of the four traits or for the area covered by a pasture.

Recently the system has changed, caused by internal and external forces. For instance, forced resettlement by the South-African government to the Omuhonga Basin in the seventies of the past century (cf. Bollig, 1997) led to severe signs of degradation in this region (Sander et al., 1998; Welle, 2003). Population and livestock number increased, thereby raising the pressure on the pasture. Causes were an improved health system and an ongoing installation of new boreholes. Hence reserves for drought are no longer held back. Former dry season pastures become permanently used to some extent, because of new income possibilities from tourist camps situated nearby. Arrangements between herdsmen become less usual.

Further changes in the management regime will result from the ongoing installation of infrastructure for the sale of livestock.

4.3.2 Model

Purpose

The model description follows the PSCP+3 protocol for describing individual- respectively agent-based models (Grimm et al., unpublished manuscript, Grimm and Railsback, 2005) and consists of six elements. The first three elements provide an overview and the remaining elements give details on model structure.

Structure and scales

The model is based on central rules of the traditional range management and on ecological consequences of cattle grazing for pasture productivity. The pasture utilised by the user group of the village Omuramba in north-western Kunene Region with an area of 40x40 km is modelled. The area under investigation is represented by a grid of 6400 cells with a cell size of 25 ha.

A habitat cell is characterised by its soil type and vegetation state (Table 4.1). Three soil types are distinguished: (1) "deep soil", (2) "shallow soil" and (3) "unsuitable soil". For the grass layer vegetation, two functional components are differentiated: firstly annual grasses and forbs, and secondly perennial grasses. Both annual and perennial grasses are characterized (1) by the amount of palatable "green biomass" produced within a particular vegetation period, which serves as forage for livestock and the perennials by (2) the reserve biomass (termed after Noy-Meir, 1982). This characteristic is measured via the ground cover of perennial grasses and represents vegetation vitality and, hence, the rain and grazing management history (O'Connor, 1991). And finally, both plant functional types have (3) a status of the soil seed bank for each grid cell. Seed bank could also be seen as a part of the reserve biomass.

The livestock is modelled as herd and characterized by its size.

The grazing management strategy maintained during the whole modelled time span is indicated by two components: (1) by the time of pasture use (all year round; only in dry season; no use) and (2) to which extent purchase of livestock is allowed.

Pastures are characterised by a fixed proportion of habitat cells with a similar soil type. In this spatially implicit model, the location of the cell on the grid is not considered. In each cell of a pasture the same grazing strategy is applied. Four pasture types are differentiated: "rainy season pasture" (RSP), "dry season pasture" (DSP), "reserve for drought" (RFD) and "area unsuitable for grazing" (UFG). One time step represents one year, starting in November with the onset of the rainy season. In reality the presented traditional grazing strategy was only applied up to 40 years. Hence, it cannot be judged whether this strategy was sustainable. The modelled time span was chosen to be longer than the planning horizon of the pastoralists and on a scale in which grazing impact on the vegetation is visible. Hence, a time span 100 years is modelled after the onset of grazing.

Table 4.1: Full set of state variables in the model

	Name of variable		Units
Habitat	Soil type of cell i	st_i	three types (deep, shallow, unsuitable)
Precipitation	Amount per year	$r(t)$	4 classes
Vegetation			
Grass layer (1): Fodder production	Green biomass per cell i	$b_i^{per}(t)$ $b_i^{ann}(t)$	t/ha
Grass layer (2): Reserve biomass of perennial grasses	Perennial ground cover per cell i	$c_i(t)$	4 classes (%)
Grass layer (3): Status of soil seed bank	Depletion level of soil seed bank per cell i	$sb_i^{per}(t)$ $sb_i^{ann}(t)$	$0, 1, \ldots, sl_{per}$ $0, 1, \ldots, sl_{ann}$
Pasture (4 types)	Available biomass for livestock	$b_{av}^{past}(t)$	t
	Required biomass for livestock	$b_{req}^{past}(t)$	t
Management	Trad. Strategy/ Alternative Strategy	T, A1, A2, A3	4 types
	Purchase	no, P_1, P_2	3 types
Livestock	Number	$n(t)$	number in TLU[1]
	Purchased number of animals	$n_{purch}(t)$	number in TLU

[1] Abbreviations: TLU - Tropical Livestock Unit

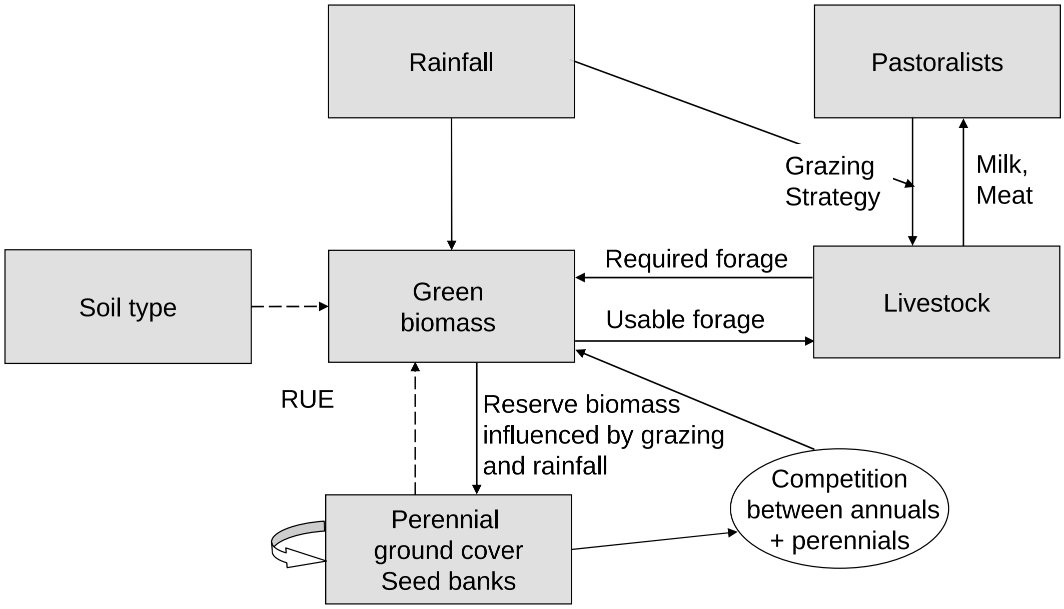

Figure 4.4: Causal diagram indicating the influential factors on vegetation and livestock dynamics in the model. Current rainfall is translated into green biomass according to the Rain Use Efficiency (RUE). This parameter depends in this study on soil type, perennial ground cover and on longevity of the two seed banks. The perennial ground cover is affected in reality by current rainfall and grazing only indirectly via photosynthesis of green biomass. For simplification this relationship is mapped in the model rule directly (cf. Table 4.8).

Process overview and scheduling

In this paragraph the processes of the model are shortly specified to allow a general overview of the model and the dynamics. For a detailed description of each of the processes, see section "Submodels". The processes are presented according to their sequence proceeding within one time step. For the causal relations between the processes, see also Figure 4.4.

Process 1: Rainfall The precipitation of a rainy season is randomly chosen according to the underlying rainfall distribution.

Process 2: Production of green biomass (= usable forage) The green biomass of both functional types of the grass layer (annual and perennial grasses) is determined by three factors: precipitation, soil type, and in the case of perennials its previous ground cover (cf. Figure 4.4). Firstly, biomass growth of perennial grasses is modelled. Annual grasses produce biomass according to the space left by perennial grass tufts, and according to precipitation and seed bank status.

Process 3: Livestock demographics Livestock demographics in dependence on the availability of usable forage and the grazing strategy are modelled: A constant birth rate is assumed. The ratio between available and required biomass determines the grazing pressure. If available biomass is insufficient on a pasture the next pastures are used earlier. If the total available forage is insufficient, animals die/ are sold / are swapped to other herds with a certain rate.

Process 4: Feedback of grazing and rainfall on perennial ground cover (reserve biomass) At the end of a time-step the perennial ground cover (representing the reserve biomass) is adjusted. The perennial ground cover depends on (1) current rainfall, (2) grazing pressure, (3) time of grazing (in dry season or all year round) and (4) on perennial ground cover of the previous year. Finally the degree of seed bank depletion per cell is adjusted in dependence on precipitation and the probability of seed entry.

Initialisation

The proportion of the pasture types with different soil properties correspond to the pastures of the households of the village Omuramba: rainy season pasture 10%, dry season pasture 45%, reserves for drought 18% and the remaining 27% are unsuitable for grazing. Rainy season pasture (RSP) consists of cells with "deep soil". Dry season pastures (DSP), reserves for drought (RFD) and area unsuitable for grazing (UFG) consist of cells with "shallow soil". The perennial ground cover of all cells was set to "middle". In order to minimise the effect of initial conditions forty years without grazing are simulated before livestock number is initialised according to the available forage.

Sub-Models

Rainfall The highly stochastic precipitation is modelled using four classes, with r_{mean} indicating the long-term mean of the annual rainfall. As no sufficient data are available on Omuramba, the frequency distribution of the relative deviations is taken from Ombulantu, a site 200 km to the east. The mean annual rainfall of Omuramba is about 280 mm/y. As rain value associated to each class, the mid-point of the class is used (Table 4.2, column 4).

Growth of green biomass As the simplest case, a linear relationship between biomass and precipitation is assumed with intercept equaling zero (Lauenroth and Sala, 1992; O'Connor et al., 2001). The slope of this function represents the Rain-Use-Efficiency (RUE). In our model, the parameter depends on habitat type (deep vs. shallow soil) and for perennial grasses on the reserve biomass of the plants

Table 4.2: Rainfall classes used in the model and underlying frequency distribution of rainfall derived from the data set of Ombalantu. Classification based on unpublished data from the Weather Bureau Windhoek, Namibia. For more details on rain frequency distributions in the Kunene Region, see Sander and Becker (2002), p.63

Class		Range	Rain values	Frequency
-2	Drought	$r(t) < 0.5 \cdot r_{mean}$	$0.25 \cdot r_{mean}$	12%
-1	Below average	$0.5 \cdot r_{mean} \leq r(t) < 0.75 \cdot r_{mean}$	$0.625 \cdot r_{mean}$	16%
0	Average	$0.75 \cdot r_{mean} \leq r(t) < 1.25 \cdot r_{mean}$	r_{mean}	43%
1	Above average	$1.25 \cdot r_{mean} \leq r(t)$	$1.375 \cdot r_{mean}$	29%

Table 4.3: Rain use efficiencies, RUE, ($\frac{tonnes}{ha \cdot mm}$) for perennial and annual grasses in dependence on soil type and ground cover $c(t)$ in time step t (in case of perennials)

	Perennials				Annuals
	$c(t) = 0$	$c(t) = 1$	$c(t) = 2$	$c(t) = 3$	
deep	0	3	4	4.8	2.78
shallow	0	1.5	2	2.4	1.35

represented by ground cover $c(t)$ (see Table 4.3). The values for annual grasses are based on empirical data of *Schmidtia kalahariensis* (A. Linstädter, unpublished data). For perennial grasses expert knowledge and specifications found in the literature are used (Le Houérou et al., 1988, p.1; Le Houérou, 1984, p.221). The applied classification of perennial cover $c(t)$ depends on the soil type (Table 4.4).

It is assumed that no green biomass is taken over from the previous year, by doing so natural decay is included implicitly in the model.

The biomass of perennials at time t is calculated by

$$b_i^{per}(t) = RUE(st_i, c_i(t)) \cdot r(t) \tag{4.1}$$

and the biomass of annuals at time t by

$$b_i^{ann}(t) = RUE(st_i) \cdot r(t) \tag{4.2}$$

for all cells i, $i = 1, \ldots, 1600$. $c_i(t)$ indicates the current perennial ground cover on i and st_i the soil type.

Table 4.4: Classification of perennial ground cover $c(t)$ (%) for deep and shallow soils. For shallow soil the perennial ground cover is assumed to be half of the range of the deep soil. A perennial ground cover higher than 90% does not occur under natural circumstances

Class		$c(t) = 0$	$c(t) = 1$	$c(t) = 2$	$c(t) = 3$
		no	low	middle	high
Perennial	deep soil	0	1-30	31-60	61-90
ground cover(%)	shallow soil	0	1-15	16-30	31-45

The interspecific competition between annual and perennial grasses is modelled implicitly. It is assumed that perennial grasses out-compete the annuals, since they occupy the available place first. Hence annuals may only occupy the space left. We assume that green biomass has an upper limit due to restricted abiotic resources such us water, nutrients, and sunlight. If the sum of annual and perennial grass biomass exceeds this limit, the biomass of the annuals is correspondingly diminished. The limit is assumed to be $cap_{dp} = 1.5$ t/ha on deep soil and $cap_{sh} =$ 1 t/ha on shallow soil (Schulte, 2002b).

For annuals hold, if the seed bank is empty on a grid cell, no green biomass is produced. Only a portion of the whole green biomass serves as forage. The causes are: grazing efficiency (the proportion of total herbage livestock can harvest) and forage loss (due to trampling, decomposition, etc.). Mostly in literature the proper use factor pf is used to cover all three aspects. Different values for pf are proposed: 0.45 - de Leeuw and Tothill (1993); 0.25-0.3 - Guevara et al. (1996, p.350); 0.5 - Le Houérou (1984, p.233) ; 0.25-0.3 - Le Houérou (1989, p.110). We use firstly $pf_{per} = pf_{ann} = 0.45$ in the model, not distinguishing between annuals and perennials. However, in a later part of the study the influence of different grazing values for annuals and perennials on the assessment of the grazing strategies is investigated carrying out a sensitivity analysis.

In a next step, the available palatable biomass - b_{av}^{past}, $past$=RSP, DSP, RFD - is calculated by summing up the biomass of annuals b_i^{ann} and perennials b_i^{per} on all cells i belonging to pasture $past$:

$$b_{av}^{past} = \sum_{i \in past} b_i^{per} \cdot pf_{per} + b_i^{ann} \cdot pf_{ann} \tag{4.3}$$

Demographics of livestock Only cattle demographics are included in the model analysis. Calving rates are 0.4 per year and cow (Bollig, 2000). Since just under 50 percent of the livestock are females, a total constant cattle growth rate of $g_c = 0.2$ is used (Bollig and Schulte, 1999). A decrease in livestock numbers is caused either by drought-induced mortality, by the consumption of meat or by renting to relatives. All these processes are summarized and modelled by a constant mortality rate $prob_{mort}$. For a detailed description under which circumstances mortality takes place in the model, we refer to the next section.

Movement and grazing of livestock The grazing strategy applied from 1960-1995 (traditional strategy) is compared to three alternative strategies. The three alternative strategies are constructed in such a way that in each case a certain aspect of the traditional strategy is altered. Hence let us look first at the

Characteristics of the traditional strategy T:

1. **Seasonal Resting on Dry Season Pastures (DSP)** (including its division in three parts (DSP1, DSP2, DSP3)):
    - Use of RSP by the whole herd in the rainy season, by lactating animals in the dry season (portion of lactating animals: $p_l = 0.2$ of the herd, Bollig and Schulte (1999, p.85))
    - Resting of dry season pastures DSP in rainy season, grazing in dry season by non-lactating animals (if the forage is insufficient on RSP, then DSP1 is used already in the rainy season)
2. **Spatial extension**,with respect to two different aspects:
    a) Use of dry season pastures DSP2, DSP3 only if DSP 1 (DSP2 respectively) is used up, otherwise these pastures are rested the whole year
    b) Reserves for drought RFD are used only if all DSP are used up, otherwise they are rested the whole year

Applying **alternative strategies** (A1), (A2) seasonal resting for DSP is dropped and both pastures (rainy and dry season pastures) are used all year round. Reserves for drought are granted with (A1), but not with (A2). Alternative strategy (A3) maintains seasonal resting of DSP and RFD, but involves a complete utilisation of the total pasture in each year (cf. Table 4.5 for a short overview of the 4 strategies).

The explicit translation of these different management strategies in model rules is made by some intermediate steps. Brief description before detailed outline: Firstly, for each pasture the respective required biomass $b_{req}^{past}(t)$, is calculated (i). Here the specific grazing strategy comes into play. Afterwards, the grazing pressure $gp^{past}(t)$ per pasture can be calculated straightforward (ii). If grazing pressure is too high, a certain action is undertaken (Table 4.6).

Table 4.5: Overview regarding the four compared strategies (T, A1, A2 and A3)

		Traditional Strategy T	Alternative Strategies A1	A2	A3
1. Seasonal Resting		yes	no	no	yes
2. Spatial extension	a) DSP	yes	no	no	no
	b) RFD	yes	yes	no	no

Table 4.6: For each pasture it is indicated which action is undertaken, if the available biomass is insufficient and hence the quotient of available and required biomass does not reach a threshold

Biomass insufficient on	Action
Rainy season pasture	Early Movement to DSP1
Dry season pasture 1 (DSP1)	Use of DSP2
Dry season pasture 2 (DSP2)	Use of DSP3
Dry season pasture 3 (DSP3)	Use of Reserve of Drought
Reserves for drought	Dying/Sale/Renting of Livestock

In detail:

Ad i) The required biomass per pasture $b_{req}^{past}(t)$ is determined by livestock number $n(t)$, amount of dry matter d, in tonnes, per TLU and year and the pasture proportion of total required biomass, $pp_{req}^{past}(t)$:

$$b_{req}^{past}(t) = d \cdot pp_{req}^{past}(t) \cdot n(t), \quad past = RSP, DSP1, DSP2, DSP3, RFD \tag{4.4}$$

The amount of dry matter d required to maintain the diet and to produce milk for one TLU per year depends on different factors (for instance on nutritive value of the forage during the seasons, and on animal race). We assumed a constant requirement of $d = 2.5$ tonnes for one TLU per year (cf. 2.3-2.7 t/y - de Leeuw and Tothill, 1993, p.78; 2.3 t/y - Guevara et al., 1993).

The proportion per pasture of total required biomass, $pp_{req}^{past}(t)$, depends on the length of the rainy season (4 months, cf. Bollig, 2002) for the two strategies which include seasonal resting (T, A3). For the two strategies with continuous grazing (A1, A2), the proportion depends on the amount of required biomass on the considered pasture in relation to total required biomass ($d \cdot n(t)$) (see Table 4.7 for details).

Table 4.7: Formula to calculate the initial portion of fodder required $pp_{req}^{RSP}(t)$ for each pasture ($past$=RSP, DSP1, DSP2, DSP3, RFD) and each grazing strategy (T- traditional, A1, A2, A3 alternatives), p_l indicates the portion of lactating animals, b_{av}^{past} the biomass available on the pasture at time step t. For strategy T and A1, pastures initially not intended to be grazed (DSP2, DSP3, RFD) may be in need, if biomass on the prior used pastures is insufficient (cf. Table 4.6). In this case, portion of fodder required $pp_{req}^{past}(t)$ will take values different from 0 for these pastures.

	T	A1	A2	A3
$pp_{req}^{RSP}(t)$	$\frac{4}{12} \cdot (1 - p_l(t)) + p_l(t)$	$\frac{b_{av}^{RSP}}{b_{av}^{RSP} + b_{av}^{DSP}}$	$\frac{b_{av}^{RSP}}{b_{av}^{RSP} + b_{av}^{DSP} + b_{av}^{RFD}}$	$\frac{4}{12} \cdot (1 - p_l(t)) + p_l(t)$
$pp_{req}^{DSP1}(t)$	$\frac{8}{12} \cdot (1 - p_l(t))$	$\frac{b_{av}^{DSP}}{b_{av}^{RSP} + b_{av}^{DSP}}/3$	$\frac{b_{av}^{DSP}}{b_{av}^{RSP} + b_{av}^{DSP} + b_{av}^{RFD}}/3$	$\frac{b_{av}^{DSP}}{b_{av}^{DSP} + b_{av}^{RFD}}/3 \cdot \frac{8}{12} \cdot (1 - p_l(t))$
$pp_{req}^{DSP2}(t)$	0	$\frac{b_{av}^{DSP}}{b_{av}^{RSP} + b_{av}^{DSP}}/3$	$\frac{b_{av}^{DSP}}{b_{av}^{RSP} + b_{av}^{DSP} + b_{av}^{RFD}}/3$	$\frac{b_{av}^{DSP}}{b_{av}^{DSP} + b_{av}^{RFD}}/3 \cdot \frac{8}{12} \cdot (1 - p_l(t))$
$pp_{req}^{DSP3}(t)$	0	$\frac{b_{av}^{DSP}}{b_{av}^{RSP} + b_{av}^{DSP}}/3$	$\frac{b_{av}^{DSP}}{b_{av}^{RSP} + b_{av}^{DSP} + b_{av}^{RFD}}/3$	$\frac{b_{av}^{DSP}}{b_{av}^{DSP} + b_{av}^{RFD}}/3 \cdot \frac{8}{12} \cdot (1 - p_l(t))$
$pp_{req}^{RFD}(t)$	0	0	$\frac{b_{av}^{RFD}}{b_{av}^{RSP} + b_{av}^{DSP} + b_{av}^{RFD}}$	$\frac{b_{av}^{RFD}}{b_{av}^{DSP} + b_{av}^{RFD}} \cdot \frac{8}{12} \cdot (1 - p_l(t))$

Ad ii) The grazing pressure $gp^{past}(t)$ depends on how much biomass is available, $b_{av}^{past}(t)$, compared to the required biomass $b_{req}^{past}(t)$. Hence, the ratio of both factors is calculated and compared to a threshold th_1 (this procedure is applied in the same way independent of the strategy).

Three cases may occur:

$$
\begin{aligned}
gp^{past}(t) &= \text{"heavy"}, && \text{if } \frac{b_{av}^{past}(t)}{b_{req}^{past}(t)} \leq th_1 \\
gp^{past}(t) &= \text{"moderate"}, && \text{if } \frac{b_{av}^{past}(t)}{b_{req}^{past}(t)} > th_1 \\
gp^{past}(t) &= \text{"no"}, && \text{if } b_{av}^{past}(t) = 0
\end{aligned}
\tag{4.5}
$$

In order to decide when the biomass on a pasture is insufficient and the cattle herd has to move to the next pasture, a second threshold th_2, $th_2 < th_1$, is defined. Hence, if the ratio between available and required biomass falls below this threshold th_2, an action is undertaken (cf. Table 4.6). In reality the level of milk production is used as an indicator. If insufficient milk is gained per cow, a new grazing area is looked for.

The required biomass on the next pasture is newly calculated by adding the amount of forage missing on the previous pasture. If the herd is already on the reserves for drought, a certain portion $prob_{mort} = 0.8$ of the herd is assumed to die (or, seen equivalently, to be sold or to be rented). That implies that a portion $(1 - prob_{mort})$ of the cattle herd is able to cope with shortages of forage by other means (e.g. browsing seeds and leaves of trees and using fat reserves).

The status variable grazing pressure is determined, apart from strength of grazing, by the time of grazing. If a pasture was used already in the rainy season, the status of grazing pressure is set to "grazing in rainy and dry season". This holds, even if the time span for the use of the pasture during the rainy season is short. If the pasture is grazed exclusively in the dry season, the status of grazing pressure is set to "grazing only in dry season". Hence, combined with the strength of grazing, $gp^{past}(t)$ may take five values: (1) "no grazing pressure", (2) "moderate (only in dry season)", (3) "heavy (only in dry season)", (4) "moderate (rainy + dry season)", (5) "heavy (rainy + dry season)". These five level of grazing pressure will involve different impacts on the dynamics of perennials and annuals (see paragraphs below).

Alternative scenarios are modelled, whereby purchase of livestock is part of the management strategy.

Two purchase strategies are compared:

(P1) Purchase, but without using the reserves for drought.

(P2) Purchase, with using the reserves for drought.

The number of animals purchased is determined according to the following rule: Animals are purchased as long as the mean pressure on the whole territory stays moderate. That means that the purchase of animals $n_{purch}(t)$ is carried out as long as ratio of total available and total required biomass is higher than threshold th_1. For strategy (P1) the total biomass without RFD is used, for (P2) the total biomass with RFD.

Long term condition of perennials The ground cover of the perennial grasses $c(t)$ depends on four factors: (1) current precipitation, (2) grazing pressure, (3) time of grazing (only in dry season or all year round) and (4) perennial ground cover of the previous year $c(t-1)$ (cf. Figure 4.4). In Table 4.8 the dynamics of perennial ground cover in dependence on these four factors is listed. They are assumed to be the same for deep and shallow soil. The values originate from either empirical investigation (A. Linstädter unpublished data) or from expert knowledge. For a detailed justification of the values for each single case see Appendix 4.6.

Seed bank dynamics We assume that the seed bank of perennials decrease either by germination or by natural decay of seeds. Replenishment from inside the habitat cell i can only take place if the perennial ground cover $c(t)$ in cell i is not zero. If $c(t)$ is zero, a counter, reflecting the depletion of the seed bank in cell i, is incremented by one. If the counter passes a certain threshold sl_{per}, the seed bank of the cell is assumed to be empty. Only if the seed bank is not empty (counter$< sl_{per}$) and rainfall high enough, the perennial ground cover may rise from class 0 to class 1 (cf. Table 4.8). In this case the seed bank is assumed to be refilled and the counter is reset to zero.

The dynamics of the seed bank of the annuals are modelled in a corresponding manner. But here holds that only under high grazing pressure and low rainfall at the same time, the seed bank decreases. However, already one year with at least average rainfall or only "moderate" grazing pressure resets the counter to zero. Here again, if the counter passes a certain threshold sl_{ann}, the seed bank is assumed to be empty for that cell.

Recolonisation of prior empty cells is modelled in a very simple manner. Whenever one cell exists somewhere on the grid, where the perennials/annuals are not extinct, each empty cell may be recolonised with a certain probability $prob_{per}^{entry}$, $prob_{ann}^{entry}$, for both plant functional types respectively, in years with at least average rainfall.

Table 4.8: Adjustment of perennial ground cover $c(t)$ for each cell at time t in dependence on previous ground cover $c(t-1)$, current precipitation, grazing pressure (including time of grazing). Five types of grazing pressures are differentiated (no grazing (1); grazing the whole year: moderate (2)/ heavy (3); grazing only during dry season moderate (4)/ heavy (5))

		Grazing pressure (rainy season+ dry season)											
		No				Moderate				Heavy			
Previous ground cover		0	1	2	3	0	1	2	3	0	1	2	3
Precipitation	Above average	1	2	3	3	1	1	2	2	0	1	1	1
	Average	1	1	2	3	0	0	1	1	0	0	1	1
	Below average	0	1	2	3	0	0	1	1	0	0	0	0
	Drought	0	0	1	2	0	0	0	1	0	0	0	0

		Grazing pressure (only in dry season)											
		No				Moderate				Heavy			
Previous ground cover		0	1	2	3	0	1	2	3	0	1	2	3
Precipitation	Above average	1	2	3	3	1	2	2	3	1	1	2	3
	Average	1	1	2	3	0	1	2	3	0	1	1	2
	Below average	0	1	2	3	0	0	1	2	0	0	1	1
	Drought	0	0	1	2	0	0	1	2	0	0	0	1

Parameter set In Table 4.9 the names of all parameters of the model, their values and their ranges in the sensitivity analysis are displayed.

Computer experiments

Sensitivity analysis The superiority of grazing strategy T compared to the others may depend on the chosen parameter set. For that reason most of the parameters listed in Table 4.9 were varied in a suitable range (cf. Table 4.9, column 4). Using latin hypercube sampling, 200 parameter sets were generated using the software SIMLAB 2.2 (Saltelli et al., 2004). This method, by stratifying the input space into N desired strata, ensures that each input factor has all portions of its distribution represented by input values. In this case, uniform distributions in the indicated ranges are assumed.

Table 4.9: List of parameters, default parameter set and parameter ranges for sensitivity analysis

Parameter	Abbre-viation	Value	Parameter range or value for sensitivity analysis
Total pasture size in km^2		1600	1600
Portion of RSP	a^{RSP}	0.18	0-0.55
Portion of DSP	a^{DSP}	0.37	0-0.55
Portion of RFD	a^{RFD}	0.18	0-0.55
Portion of UFG	a^{UFG}	0.27	0.27
Recolonisation probability for annuals	$prob_{ann}^{entry}$	0.5	0-1
Recolonisation probability for perennials	$prob_{per}^{entry}$	0.5	0-1
Seed bank longevity of the annuals in years	sl_{ann}	10	1-10
Seed bank longevity of the perennials in years	sl_{per}	10	1-10
Threshold 1 (respective ratio between available and required biomass)	th_1	1.5	0.5-3
Threshold 2 (respective ratio between available and required biomass)	th_2	0.9	$th_1 \cdot 0.75$
Dry matter intake in tonnes per TLU (Tropical Livestock Unit) and year	d	2.5	1-4
Proper use factor for perennial grasses	pf_{per}	0.45	0-1
Proper use factor for annual grasses	pf_{ann}	0.45	0-1
Mean annual precipitation in mm	r_{mean}	280	280
Mortality rate of livestock	$prob_{mort}$	0.8	0.4-1
Cattle growth rate	g_c	0.2	0-1
Capacity limit of grass biomass per cell in t/ha on deep soil	cap_{dp}	2	1-4
Capacity limit of grass biomass per cell in t/ha on shallow soil	cap_{sh}	1	$cap_{dp}/2$
Portion of lactating animals	p_l	0.2	0.2

For each of the parameter sets the output variables (i) mean cattle number, (ii) mean perennial ground cover, and (iii) mean biomass of annuals and perennials were calculated for the four considered strategies (T, A1, A2, A3) after 100 years of grazing, over 5000 runs. Different proper use factor of perennials pf_{per} and annuals pf_{ann} were compared since the grazing values of certain grasses (for instance *Schmidtia kalahariensis*) differ with respect to the rangeland ecologists' view and the local view of Himba herdsmen (Bollig and Schulte, 1999). Furthermore, since we have no information about the particular soil seed bank dynamics, the parameters describing longevity of the seed bank of annuals respectively of perennials were varied.

4.4 Results

4.4.1 Traditional strategy on the long run

One random run

One main objective of our model is to investigate the sustainability of the traditional pastoral-nomadic land management practised by the Ova-Himba till 1995. Hence the long-term impact of the strategy on pasture quality was evaluated. For a better understanding of the model, one randomly chosen rainfall scenario drawn from the assumed rainfall distribution is mapped for 100 years. For this scenario, cattle number, green biomass of annual and perennial grasses on the different pasture types (Figure 4.5) and the perennial ground cover (Figure 4.6) are all calculated.

During the first 40 years no grazing takes place (Figure 4.5b). The results indicate that without grazing all pastures are dominated by perennials (Figure 4.5c)-e)). After the onset of grazing, the pasture shifts from perennial to annual dominance. In both cases - with and without grazing - biomass is highly dependent on stochastic rainfall. Due to the close connection between rainfall, available forage and livestock demography, cattle numbers also reflect precipitation dynamics. After a long drought (year 43-45) livestock numbers need some time to recover. The influence of grazing is highest on RSP and DSP1. Here the perennial ground cover is zero in almost every year.

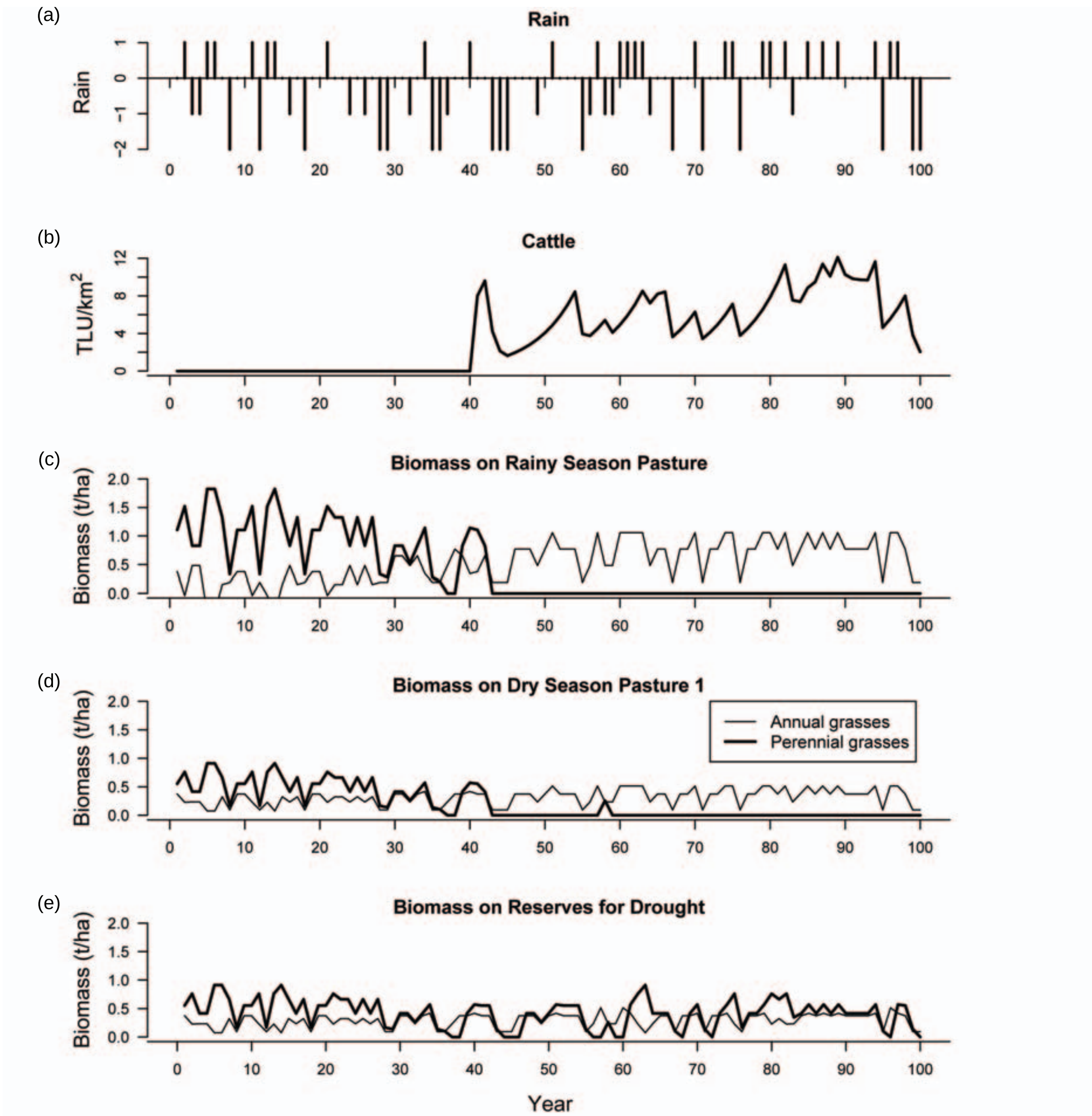

Figure 4.5: a) Rain (measured in classes, see Table 4.2), b) cattle number, c)-e) biomass production of annuals and perennials for one random simulation run on different pastures, mapped for 100 years, first 40 years without grazing (Parameter set cf. Table 4.9).

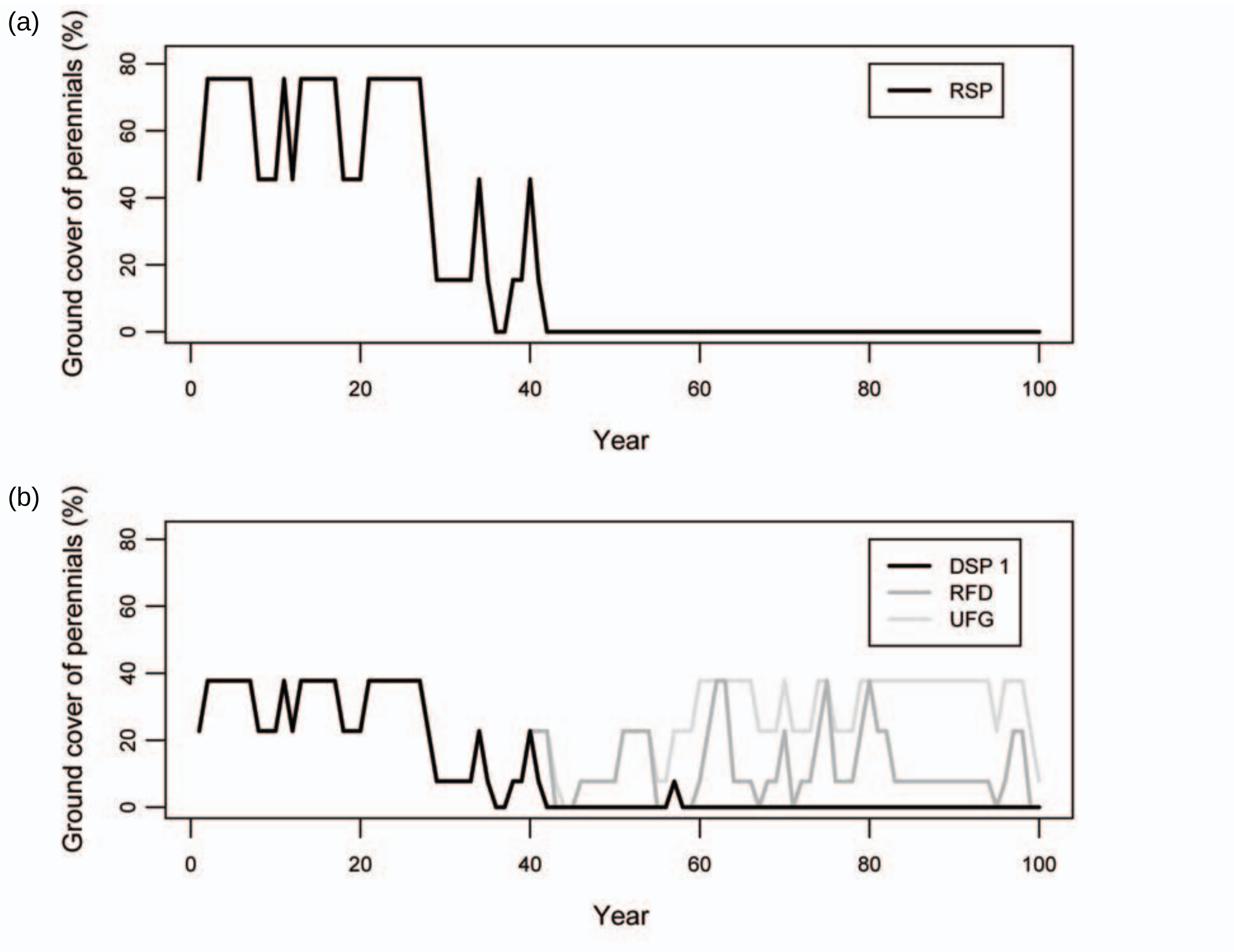

Figure 4.6: Perennial ground cover for the rain scenario shown in Figure 4.5a for different pastures (parameter set cf. Table 4.9) (Abbreviation: RSP - Rainy Season Pasture, DSP - Dry Season Pasture, RFD - Reserves For Drought, UFG - Area unsuitable for grazing). Note that in Figure b) the first 40 years are without grazing and ground cover overlaps during this time span for DSP, RFD and UFG.

The perennial ground cover of the first DSP (situated on shallow soil) lies between 0 and 7% (cf. Figure 4.6). On the other DSP (not mapped) and the RFD the perennial ground cover is higher due to less grazing pressure. During multi-year droughts (years 43-45) the perennial ground cover, even on pastures not used for grazing (UFG), reaches 0. Regarding only the used pastures (RSP, DSP, RFD), it becomes not clear whether the decrease of ground cover and of biomass of the perennial grasses (years 43-45) is a result of grazing or of drought conditions. Therefore, in the following paragraph the attempt is made to separate grazing and drought effects.

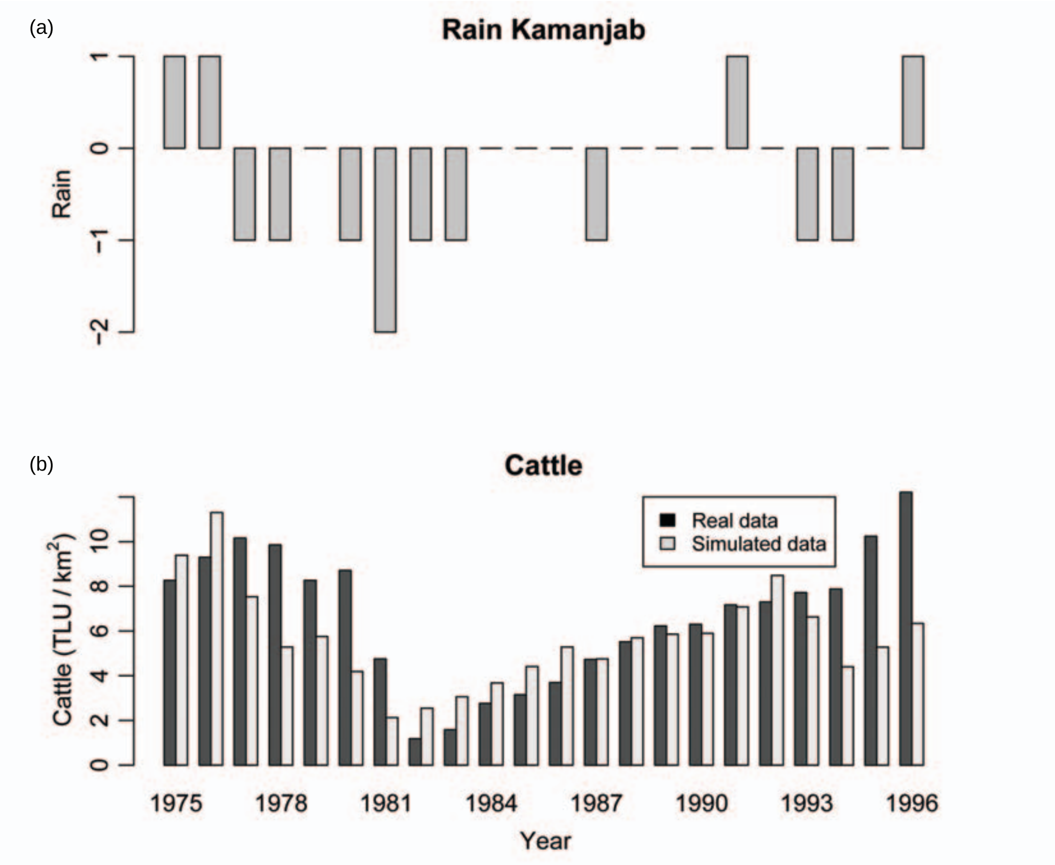

Figure 4.7: a) Rainfall in Kamanjab (source: unpublished data from the Weather Bureau Windhoek, Namibia) b) Cattle number simulated for rainfall data from Kamanjab compared to cattle data from Bollig (2002), p.191.

The classification of the perennial ground cover into only four classes apparently leads to dynamics that are more pronounced than dynamics would be based on a more detailed classification. For instance, in our model an increase of perennial ground cover from 0 to 7% can take place within only one year on rainy season pastures. This recovery would take more time in reality.

Model calibration

In order to validate the model it is helpful to compare model outcome to existing data. For the Omuramba region data were available for the 1994/1995 season (12000 cattle on 1520 km^2, cf. Casimir and Bollig, 2002, p.217). For the whole northern Kunene Region continuous cattle data are available for the time span

1975-1995 (Bollig, 2002, p.191) from censuses of vaccination campaigns (on 55 000 km^2). The data of the whole area can not be simply downscaled, since the landscape configuration differs strongly inside the northern Kunene region. For downscaling the following procedure was carried out: It is assumed that the dynamics in Omuramba area are the same as on the whole region, however with the use of Omuramba data 1994 as a benchmark (12 000 cattle on 1520 km^2 equals 7.89 TLU/km^2). Consequently, the livestock density (TLU/km^2) in Omuramba for the other years can be extrapolated from the data in Bollig (2002).

Afterwards these data are compared to the simulated cattle number (Figure 4.7).

Rainfall data are used from the Kamanjab station situated ca. 300 km south-east of Omuramba (source: unpublished data from the Weather Bureau Windhoek, Namibia). The correlation coefficient between the two data series ($R^2 = 0.58$) indicates that the model adequately describes the cattle dynamics. However for two time spans, 1975-1976 and 1995-1996, the model underestimates (overestimates respectively) the cattle numbers. The deviation in the mid-nineties most likely results from the distribution of supplementary feeding of molasse by the Namibian government.

Average model behaviour

It is necessary to separate the influence from grazing and from rainfall variability on biomass dynamics. By a high number of repeated runs (5000) with different rainfall scenarios based on the same rainfall distribution, the impact of the particular order of rain events is eliminated. With grazing, mean perennial ground cover reaches a steady state after a short time, since the seed bank is assumed in this analysis to be very long (Figure 4.8, Table 4.9). It shows that grazing has a high impact on all pasture types. The mean perennial ground cover is lowest for RSP (perennial ground cover near zero), it increases as the pasture is used less. The values correspond to ecological field data from the study site Omuramba (Schulte, 2002b; Linstädter et al. 2005 in prep.)

The impact of grazing on perennial ground cover can be translated into the amount of biomass produced by perennial grasses and - due to the competitive connection between the two functional groups - to the biomass produced by annuals (Figures 4.9a, 4.9b). With grazing, the dominance of perennial grasses changes to a dominance of annual grasses on all pastures. The lower mean biomass production on DSP and RFD is caused by the lower rain use efficiency on shallow soils compared to RSP which are located on deep soils.

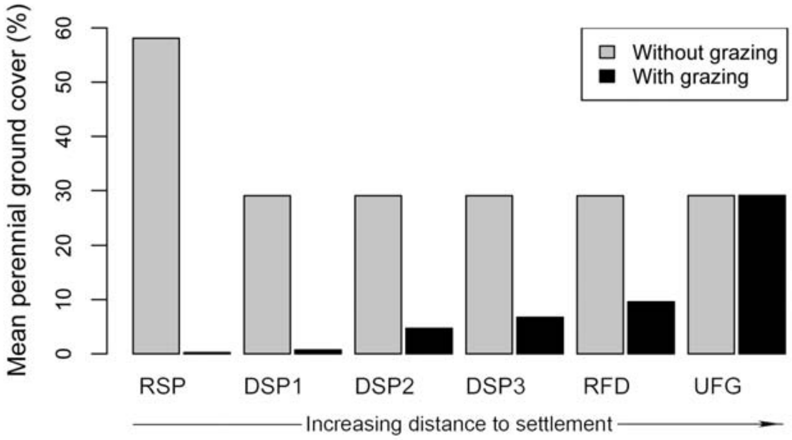

Figure 4.8: Mean perennial ground cover over 5000 runs, in the steady state, for different pastures without and with grazing applying strategy T (Parameter set cf. Table 4.9; Abbreviations: RSP - Rainy Season Pasture, DSP - Dry Season Pasture, RFD - Reserves For Drought, UFG - Area unsuitable for grazing).

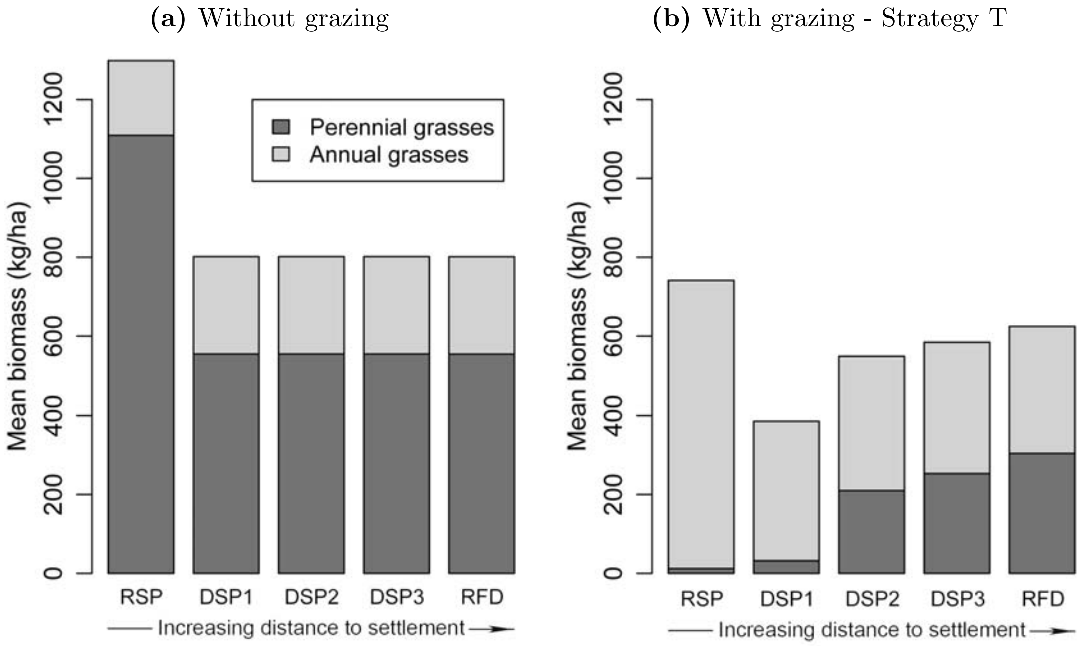

Figure 4.9: Mean biomass production for annuals and perennials grasses in the steady state for different pasture types over 5000 runs for traditional strategy T, (a) Without grazing, (b) With grazing applying strategy T (Parameter set cf. Table 4.9; Abbreviations: RSP - Rainy Season Pasture, DSP - Dry Season Pasture, RFD - Reserves For Drought).

4.4.2 Comparison of traditional grazing strategy with alternative strategies

The assessment whether the traditional management strategy can be judged as sustainable depends strongly on the sustainability criterion. Regarding for example species composition on the RSP the traditional grazing strategy can not be judged as sustainable. However, the productivity of the pastures does not decrease over time. By comparison with alternative strategies, it can be firstly analysed whether the traditional one is more suitable or not. Secondly, it can be understood whether components of the traditional management system exist which should be either maintained or discontinued since they are of less importance with respect to the considered criteria.

In Figure 4.10 it is displayed to which percentage which grazing pressure is realised for the four different strategies averaged over 5000 simulation runs and over the whole time span. It is apparent that applying the traditional strategy (T) grazing pressure is quite heterogeneous. Heavy grazing impact all year round takes place on RSP. The first dry season pasture is used in part already in the rainy season. DSP2, DSP3, RFD are not used in every year and if so, then only in the dry season. The alternative strategy (A1) and, even more, (A2) release pressure on the rainy season pastures, but the DSP are used continuously now and not seasonally. Alternative strategy (A3) shows a heterogeneous grazing pressure comparable to T, without any whole-year-resting.

For all four strategies, the mean state of perennial ground cover, mean green biomass of annuals and perennials and mean cattle number at the end of the considered time horizon of 100 years grazing are calculated (averaged over 5000 runs, Tables 4.10, 4.11).

Applying the alternative strategies with more homogeneous use, the perennial ground cover augments on RSP and partly on DSP1, but decreases in general on the other pastures (DSP, RFD). This result is carried forward on the perennial biomass.

The reduction of total perennial biomass goes along with a slight increment of total annual biomass. However, considering total biomass, the traditional strategy, including spatial and temporal heterogeneous use, has the highest production.

The crucial economic criteria - the cattle number - identifies the traditional strategy T as the strategy which guarantees the highest cattle number, due to the rest for DSP and RFD during the rainy season and possibility of spatial extension (Figure 4.11 oP - without Purchase). Using all pastures except RFD all year

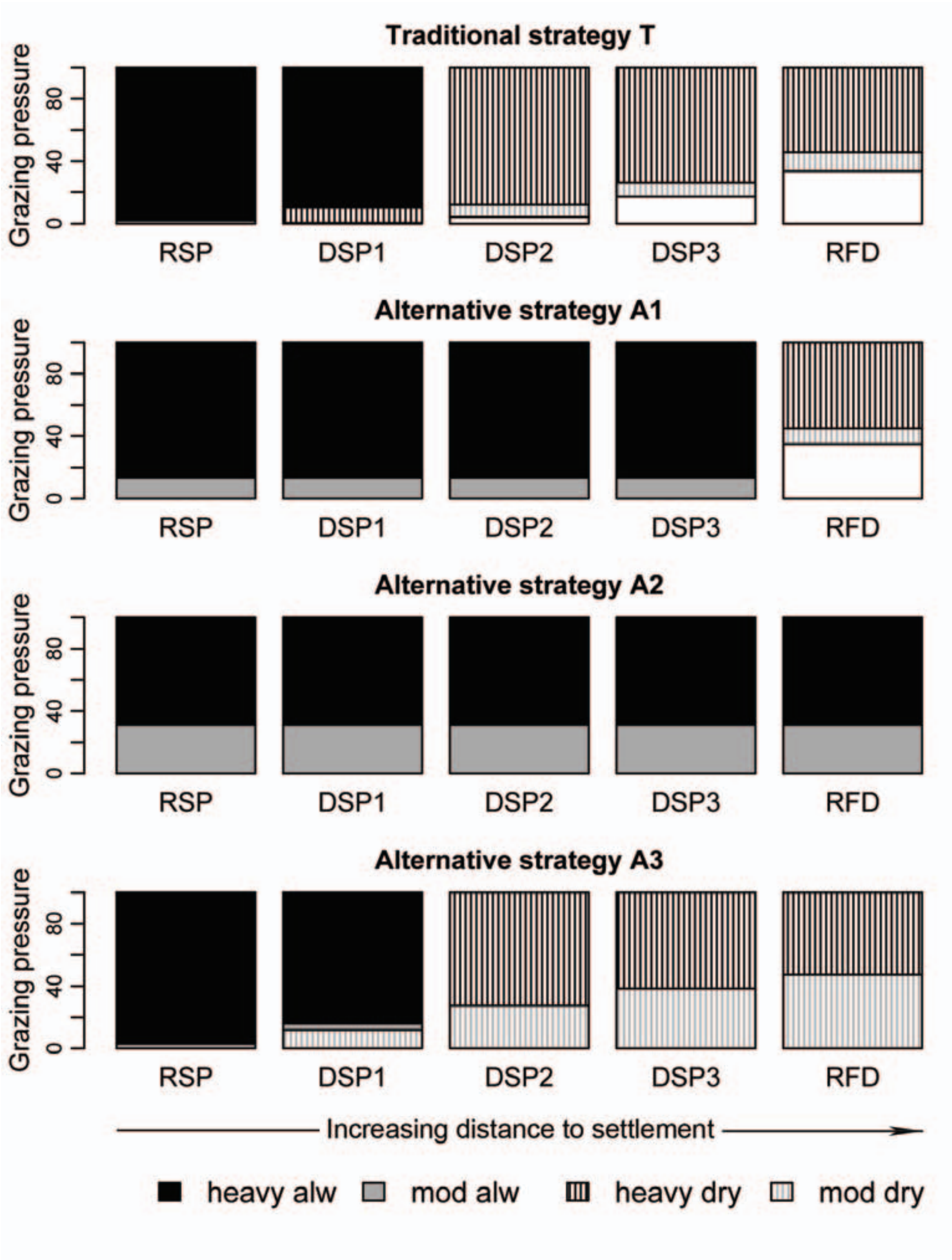

Figure 4.10: Resulting mean grazing pressure in percent on the different pastures applying traditional grazing strategy T versus alternative strategies A1, A2 and A3, calculated over 5000 runs and averaged over the whole time span (Parameter set cf. Table 4.9). The abbreviations indicate: "heavy alw" - heavy grazing the whole year, "mod alw" - moderate grazing the whole year, "heavy dry" - heavy grazing in dry season + resting in rainy season, "mod dry" - moderate grazing in dry season + resting in rainy season, "no" - no grazing.

Table 4.10: Mean cattle number, mean perennial ground cover for RSP (Rainy season pasture), DSP1 (first dry season pasture) and RFD (Reserve for drought) after 100 years of grazing averaged over 5000 runs for the traditional strategy T compared to the alternative strategies A1, A2, A3

	Mean cattle number $E(n)$	Mean perennial ground cover $E(c)$				
		RSP	DSP1	DSP2	DSP3	RFD
T	7100	0.2	0.7	4.6	6.5	9.2
A1	5680	1.1	0.6	0.6	0.6	8.8
A2	4410	2.3	1.2	1.2	1.2	1.2
A3	6780	0.3	1.1	5.1	5.8	6.2

Table 4.11: Mean available biomass of annuals and perennials (kg/ha) for RSP (Rainy season pasture), DSP1 (first dry season pasture) and RFD (Reserve for drought) after 100 years of grazing averaged over 5000 runs for the traditional strategy T compared to the alternative strategies A1, A2, A3

	Mean available biomass $E(b_{av}^{past})$							
	total		RSP		DSP1		RFD	
	ann[1]	per	ann	per	ann	per	ann	per
T	385	174	721	9	349	34	318	295
A1	391	100	705	57	349	29	319	301
A2	393	66	685	117	347	58	347	58
A3	388	157	719	15	347	46	329	227

[1] Abbreviations: "ann" - annual grasses and forbs, "per" - perennial grasses

round (A1) diminishes the cattle number on average by almost 20%. Without the protection of RFD (A2), the reduction of livestock compared to T is 29%. As long as on DSP and on former RFD resting is granted during the rainy season (A3), the cattle number decreases only slightly compared to T. Hence, of highest importance is the granting of rest periods during the rainy season for parts of the pasture.

4.4.3 Purchase of livestock

We were interested in understanding what influence is exerted by a change in the underlying socio-economic conditions. We took as an example the access to purchase markets of livestock. The results over 5000 simulation runs are depicted

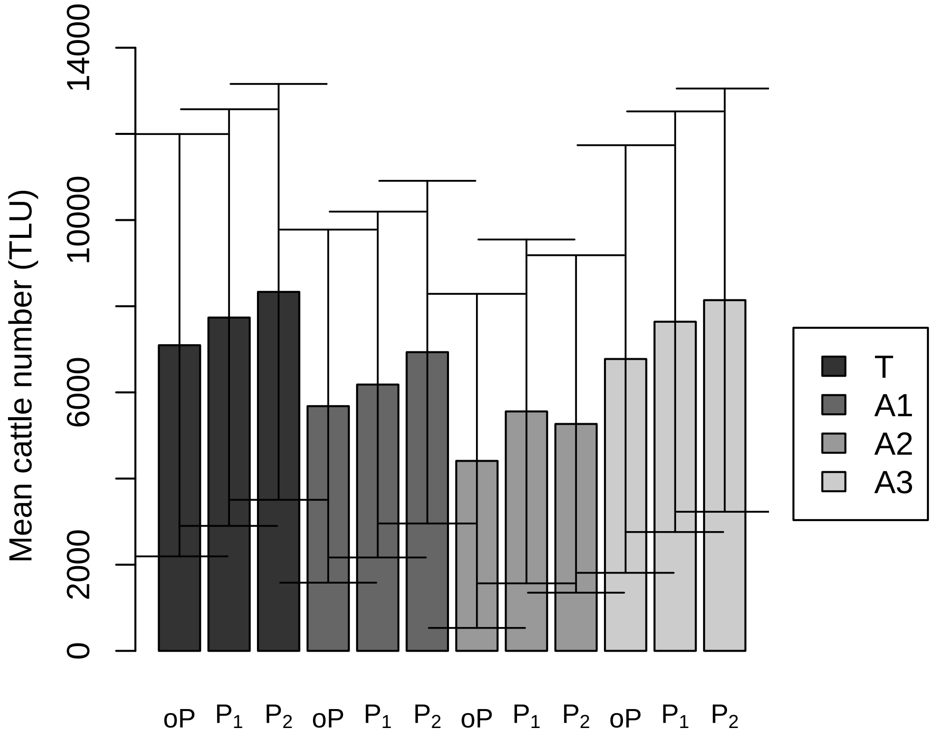

Figure 4.11: Case of livestock purchase: Mean cattle number and standard deviation in TLU (Tropical Livestock Unit), applying traditional grazing strategy T and alternative strategies A1, A2 and A3 averaged over 5000 runs after 100 years of grazing (Parameter set cf. Table 4.9, oP - without purchase, P1 - purchase without using reserves for drought, P2 - purchase with using reserves for drought).

in Figure 4.11. Remember, purchase is only allowed as long as grazing pressure stays moderate.

Purchase applying under traditional strategy T, leads to a higher livestock number. The biomass can be used more effectively now - After a drought and low cattle numbers, the livestock can be restocked.

Applying alternative strategy A1, purchase can increase livestock numbers (oP 5684, P1 6182, P2 6934 cattle), but these will still be lower than livestock numbers achieved under traditional strategy without access to purchase markets (7095 cattle). Under strategy A2 the cattle number even decreases applying purchase strategy P2. In this case, the positive effect on the cattle number by the possibility of purchase is reduced by the negative effect on biomass production through not resting of DSP and RFD in the rainy season and no resting of RFD the whole year. Under A3 (with the granting of rest periods during rainy season) almost as many livestock can be kept as when applying the traditional strategy.

4.4.4 Sensitivity analysis

Conducting a sensitivity analysis, the question is addressed how strongly the superiority of the traditional strategy T, when compared to alternative strategies A1, A2, A3, depends on the chosen parameter set. From the 200 by Latin-hypercube sampling generated parameter sets, those were determined, where alternative strategies (A1, A2, A3) resulted in higher mean cattle numbers (averaged over 5000 runs after 100 years of grazing) than the traditional strategy T.

The results show that the application of the traditional strategy T leads to a higher livestock number for 91% of all parameter sets (not presented here in detail). The 9% of parameter sets where one of the alternative strategies is superior were caused by one or a combination of the following three reasons:

(a) Threshold 1 and 2 respective ratio between available biomass to required biomass, th_1 and th_2, are relatively small ($th_1 < 0.7, th_2 < 0.5$).

(b) Proper use factor of perennials, pf_{per}, is much smaller than the one of annuals pf_{ann}.

(c) Portion of dry season pasture (DSP), a^{DSP}, is very small (increase of RSP accordingly).

Ad a) These low values of th_1, th_2 seem not to be realistic.

Ad b) The alternative strategies lead to a higher portion of annuals. Hence, a much higher proper use factor of annuals compared to perennials impose higher cattle numbers for the alternative strategies. This assumption seems to us non-realistic to us (see discussion section of this study).

Ad c) For an extremely small portion of dry season pasture, the positive effect of resting during the rainy season on DSP applying T is negligible and the negative effect of high pressure on RSP predominates. It is an extreme case of the considered parameters set.

Summarising the predominance of the Traditional Strategy (T) holds under realistic parameter ranges.

4.5 Discussion

4.5.1 Role of heterogeneous pasture use

The central question of our study was to identify components of the traditional Ova-Himba strategy (practised from 1960-1995) essential for sustainability. Our approach: We compared the traditional strategy with strategies where particular aspects were altered. This is currently extremely relevant: Since the mid-nineties, certain parts of the former practised strategies are changed. For instance, the protection of reserves for drought and the coordination of movements to dry season pastures are partly abandoned.

In our analysis two components of the traditional strategy were detected as crucial for high biomass production:

1. Intra-annual heterogeneity of resource use: resting of the dry season pastures during the rainy season.

2. Inter-annual heterogeneity of resource use: granting of reserves for drought and use of dry season pastures situated further away only if the closer ones are used up.

Let us consider these two components more in detail:

(1) Resting of pastures during the rainy season: The traditional system is characterised by a continuous high grazing pressure close to the permanent settlements and a resting of dry season pastures (DSP) during the rainy season. In our model, this system was compared to a homogeneous and continuous pasture use. The comparison of both strategies revealed a trade-off effect: Homogenous pasture use relieves pressure on the rainy season pastures, but increases the pressure on DSP and allows no resting in these areas. Model results suggest that the resting of the dry season pastures during the rainy season is particularly important. It leads to a higher regeneration potential for the biomass. Furthermore, the plant populations of the grasses can produce higher numbers of seeds. With continuous land use this regeneration potential is strongly reduced, especially under heavy grazing pressure. Our findings are supported by other studies in semi-arid range lands (by Oba et al., 2001, p.836; Sternberg et al., 2000). Resting during the rainy season promotes biomass production, flowering and seedling success of the grasses (O'Connor and Everson, 1998). The importance of an appropriate timing of resting is widely acknowledged (among them Hanley, 1979; Westoby et al., 1989; Hary et al., 1996; Stafford Smith, 1996; Niamir-Fuller and Turner, 1999; Tainton and Danckwerts, 1999).

(2) Granting of reserves for drought: Conserving pastures for times of drought is shown to be of ecological and economic significance (cf. Niamir-Fuller, 2000). They are key resources in years with scarce forage (Scoones, 1995). Hence, the fluctuations in rainfall are not directly carried over to forage availability and livestock number - a smoothing in stock numbers over the years is the result. Furthermore, the reserves for drought and DSP located further away are not used in wet years and hence rested effectively. In Chapter 2 of this thesis a sophisticated range management system practised on a commercial farm in Namibia is analysed and discussed. It showed that biomass production benefits considerably from resting periods in wet years, because vegetation can regenerate more effectively under these favourable growing conditions.

Summarizing, the traditional Ova-Himba management system is based on a spatially and temporally heterogeneous use of pastures. Its success has two aspects: (1) flexibility and (2) restriction. The herders extended the spatial range of use flexibly, but were restricted in time and order of pasture use. This management system led to an effective build up and use of an ecological buffer of the system - the reserve biomass (cf. Wiegand et al., 2004). However, it is not easy to judge whether the traditional system of the Ova-Himba can be termed sustainable. It is a multilayered problem and depends on the considered scale: On a small scale the rainy season pastures are covered exclusively by annuals and are prone to degradation. But on the scale of the total system, the productivity is maintained.

Why do pastoralists apply a heterogeneous land use? Numerous pastoralists worldwide apply management strategies where pastures are rested during the rainy season for the use in the dry season (e.g. Turkana of Kenya, Jie of Uganda, cf. Coughenour, 1991). Often it is not the explicit management purpose to rest the vegetation during the rainy season. Other aspects of land use unintentionally cause this grazing regime - above all water availability. During the rainy season, higher productive areas are used, where water is only available temporally. If pasture areas are situated at a larger distance from water points, they are not used annually and, therefore, rested. Further reasons for irregular land use patterns in arid regions worldwide may be the unavailability of forage, the danger of disease transmission by tsetse flies or ticks, and low temperature (Niamir-Fuller and Turner, 1999). Steep mountain pastures not accessible for cattle are a key factor for the successful use of spatially heterogeneous rangelands. Medium-distance seed dispersal (several km for anemochorous dispersal units) from these areas may insure the recolonisation of degraded areas with locally depleted soil seed banks. Reserves for drought, which are difficult to access and have limited water resources, have the same ecological function.

Some remarks on the assumptions and limitations of the model: Our results are robust even if parameter sets are varied in realistic ranges. Some exceptions are rendered by a detailed sensitivity analysis. It shows that results are strongly dependent on the proper use factor of annual grasses compared to perennial grasses. On the study site, the perception of grazing values of the annual grass species *Schmidtia kalahariensis* and of the perennial species *Stipagrostis uniplumis* differs considerably between Himba herdsmen and range ecologists (Bollig and Schulte, 1999). Range ecologists consider perennial grasses to have inherently higher values than annuals, because they produce more leave material (ibid.). Investigations of the nutritional value of the two grass species on the study site support the superiority of the proper use factor of the perennial grass species (Casimir and Bollig, 2002). In sharp contrast, Ova-Himba herdsmen rank *Schmidtia k.* of high value (Bollig and Schulte, 1999).

Regarding the mobility pattern, it is assumed in this study that livestock is moved to the next dry season pasture as soon as the ratio of available and required biomass falls below a certain threshold of biomass availability. This "push-option" of pasture use, though, is accompanied by a "pull-option". If herders have the information that a good pasture is available at a close distance (due to favourable, spatially heterogeneous rainfalls), they will move to this pasture, even if the natural resources of the current pasture have not been fully exploited. This aspect will be included in a spatial-explicit model in the future. Furthermore, in such a model the aspect of erosion will be investigated threatening areas with complete disappearance of perennials.

4.5.2 What does happen to the state of the rangeland system if socio-economic conditions change?

The Ova-Himba land management is currently affected by numerous external and internal factors. From these factors, we have analysed the key factor "livestock purchase" on the vegetation composition, productivity and on herd dynamics.

Purchasing livestock - common on most commercial farms - may have both positive and detrimental effects on land use sustainability. On the one hand, livestock performance can be more effectively adapted to years with high biomass production caused by high rainfall. On the other hand, livestock purchase may disappoint the highly important but unplanned rests of the pastures in post-drought years (cf. Chapter 2 of this thesis). Unplanned rests are unintended rests for parts of the pasture: After prolonged droughts and resulting breakdowns of livestock numbers, parts of the pastures may not be needed for certain periods of time, since livestock need some time to reach pre-drought numbers. Hence an effective regeneration of these parts of the total pasture area is ensured (see Chapter 2 of this thesis and Stafford Smith and Foran, 1992).

Our study shows that livestock purchase may lead to a considerable decline in vegetation quality. However, as long as the traditional grazing strategy is maintained (which allows a rest of certain parts of the pasture in the rainy season), the decline in productivity does not affect livestock numbers considerably. The livestock number kept on the pasture augments in total. In contrast, if the land management implies continuous grazing without reserves for drought, purchase of livestock will lead to a considerable decline in pasture productivity. For the long term, less livestock can be kept on the farm compared to a scenario without purchase options.

In summary, the use of simulation models is promising for a thorough analysis of changing socio-economic conditions as well as climate change. The model allows investigation of the consequences of socio-economic changes in traditional strategies (Vetter, 2005). This approach enables us to address the even more crucial question in the future - what the (ecological and socio-economic) boundary conditions permitting sustainable land use are.

4.5.3 Analysing indigenous knowledge to contribute to the equilibrium versus non-equilibrium discussion

Interest in indigenous knowledge has been growing in recent years, due to a recognition of its relevance for sustainable resource use (Berkes et al., 2000). In this field, indigenous knowledge can often be only observed in practised actions. Here, simulation models can help to connect indigenous to scientific knowledge: They allow the investigation of the significance of certain components of traditional management strategies for sustainability. This fosters a comprehensive understanding of underlying dynamics. Basic principles of sustainable management and its boundary conditions can be hypothesised. This is the basis for an application to other management systems.

Some remarks regarding the current equilibrium vs. non-equilibrium discussion: Semi-arid ecosystems are primarily driven by fluctuating rainfall, which masks the effects of grazing on vegetation productivity (Stafford Smith, 1996). This may lead to under- or overestimation of grazing impact (Niamir-Fuller, 2000). Using the simulation model, in our study the influence of rainfall fluctuations and grazing on pasture dynamics could be separated. Our results substantiate the hypothesis that both, biotic and abiotic factors are essential for vegetation dynamics on different temporal and spatial scales. Firstly, the strong effect of rainfall and a recommendation for a close adaptation of livestock numbers to available forage is supported - as long as a second aspect is taken into account: the importance of timing of grazing and resting. These two aspects are shown to have strong impact on biomass production and species composition.

Secondly, Illius and O'Connor (1999) discussed the role of key resource areas for an increased risk of degradation on rainy season pastures (RSP). Our study supports this hypothesis. Caused by the inter-annual heterogeneous use, dry season pastures situated further away and reserves for drought act as key resources

(Scoones, 1995). Their availability limits livestock numbers. Degradation on rainy season pastures is higher, if key resources are readily available. Considerable shifts in dominance patterns connected with losses of productivity take place on RSP. Nevertheless, spatial and temporal heterogeneity of land use renders a higher productivity of the total system.

Summarizing, the investment into the ecological buffer of the vegetation, i.e. the reserve biomass, is crucial for the maintenance of long-term productivity in semi-arid rangelands. Therefore, two components of the traditional Ova-Himba strategy are highly significant: Intra-annual heterogeneous use which grants seasonal resting for the pasture and inter-annual heterogeneous use by granting of reserves for times of drought. These two components need to be maintained under changing conditions in the Kunene Region. Furthermore, we hypothesise that these are important basic principles for sustainable range management in semi-arid regions in general.

4.6 Appendix

Detailed explanation of the model rules regarding perennial ground cover

Recurrence of Table 4.8: Adjustment of perennial ground cover $c(t)$ for each cell at time t in dependence on previous ground cover states (0,1,2,3) $c(t-1)$, current precipitation, grazing pressure (including time of grazing)

		Grazing pressure (rainy season+ dry season)											
		No				Moderate				Heavy			
Previous ground cover		0	1	2	3	0	1	2	3	0	1	2	3
Precipitation	Above average	1	2	3	3	1	1	2	2	0	1	1	1
	Average	1	1	2	3	0	0	1	1	0	0	1	1
	Below average	0	1	2	3	0	0	1	1	0	0	0	0
	Drought	0	0	1	2	0	0	0	1	0	0	0	0

		Grazing pressure (only in dry season)											
		No				Moderate				Heavy			
Previous ground cover		0	1	2	3	0	1	2	3	0	1	2	3
Precipitation	Above average	1	2	3	3	1	2	2	3	1	1	2	3
	Average	1	1	2	3	0	1	2	3	0	1	1	2
	Below average	0	1	2	3	0	0	1	2	0	0	1	1
	Drought	0	0	1	2	0	0	1	2	0	0	0	1

Ground cover state 0 = ”none”, i.e. the perennial ground cover of the *Stipagrostis uniplumis* individuals in the grid cells is 0%. The perennial ground cover relates to the biomass cover of living parts of the tufts. It is therefore a measure for the reserve biomass of the grid cell’s grass population. If the ground cover state is zero, the grass population is extinct in the particular grid cell. This may be the case (i) because the cover state has gone down by one or more digits due to a recent damage (disturbance) of the grass layer caused by grazing and/or rainfall below average, or (ii) because the cover state has remained unchanged due to conditions not favourable enough for a significant change in ground cover state.

Ground cover state 1 = "little", i.e. the perennial ground cover of the *Stipagrostis uniplumis* individuals in the grid cells is 1-30% on deep soil or 1-15% on shallow soil. The ground cover may be "little"(i) because the cover state has gone down by one or more digits due to a recent damage (disturbance) of the grass layer caused by grazing and/or rainfall below average, or (ii) because the cover state has remained unchanged due to conditions not favourable or unfavourable enough for a significant change in ground cover state, or (iii) because the ground cover state has improved by one digit under favourable conditions due to a recolonisation from the seed bank.

Ground cover state 2 = "middle", i.e. the perennial ground cover of the *Stipagrostis uniplumis* individuals in the grid cells is 31-60% on deep soil or 16-30% on shallow soil. The ground cover may be "middle" (i) because the cover state has gone down by one or more digits due to a recent damage (disturbance) of the grass layer caused by grazing and/or rainfall below average, or (ii) because the cover state has remained unchanged due to conditions not favourable or unfavourable enough for a significant change in ground cover state, or (iii) because the ground cover state has improved by one digit under favourable conditions due to a regeneration of the grass biomass (and facultatively due to a recruitment event).

Ground cover state 3 = "high", i.e. the perennial ground cover of the *Stipagrostis uniplumis* individuals in the grid cells is 61-90% on deep soil or 31-45% on shallow soil. The ground cover may be "high" (i) because the cover state has remained unchanged due to conditions not unfavourable enough for a significant change in ground cover state, or (ii) because the ground cover state has improved by one digit under favourable conditions due to a regeneration of the grass biomass (and facultatively due to a recruitment event).

The transition rules indicating changes in ground cover state are backed by monitoring data (Schulte, 2002a,b, and Linstädter née Schulte unpublished data) and by expert knowledge based on ten years of continuous research on grass layer dynamics under different rainfall and land use conditions in Kaokoland. The sources for the particular information are indicated below, and an ecological explanation of the values is given.

Rules for "no" grazing

The transition rules where "no" grazing pressure is present can be backed by information from grazing exclosures established 1995, 1996 or 2004 in northern Kaokoland and monitored till 2005. The year 1995 had rainfall above average, 1996 had average rainfall, and 2004 had below-average rainfall. Further information comes from monitoring sites established 2003 and 2004 in protected areas of Namibia's Kunene Region, notably from a Mopane savanna in Etosha National Park (Jula Zimmermann pers. comm.).

1. **Regeneration:** In the case of good (above average) rainfall, the grass layer may regenerate. In our model, the ground cover state can only improve by one class per year. A faster inter-annual regeneration is not backed by our data (see Schulte, 2002b), possibly due to biological restrictions of maximum productivity. The transition rules suggest that, under optimum conditions, the process of full regeneration takes four years. This seems realistic if recovery speed on grazing exclosures is extrapolated from good rain years.

2. **No change:** In most years with average rainfall (not more than 25% less than the long-term mean) or rainfall 25-50% below the long-term mean, the ground cover state remains unchanged. The only exception is the regeneration of a locally extinct population even under average rainfall conditions due to a recolonisation from the soil seed bank. This is backed by data from grazing exclosures established 1996. In the case of a "drought" year (defined here as rainfall more than 50% below the long-term mean), the ground cover state is reduced by one digit, if a reduction is still possible.

Rules for "moderate" and "heavy" grazing

The transition rules for "moderate" and "heavy" grazing pressure are based on continuous monitoring data 1995-2005 from regular rainy season pastures (RSP) and from dry season pastures (DSP) in Kaokoland both with deep and shallow soil. Furthermore, data from grazing exclosures opened after four and eight years were used.

1. **Regeneration:** On DSP, a recolonisation of a pasture without living *Stipagrostis uniplumis* individuals is possible in years with good rain, both under moderate and heavy grazing pressure, because cattle can rely on the high amount of annual grass biomass. They are often moved to the next DSP before they have grazed all standing biomass. In good years, a further regeneration of a severely damaged or young grass population (ground cover state 1) can take place on these pastures under moderate grazing conditions. If the grass population of a rainy season pasture (RSP) grid cell has become extinct, it can only regenerate in years with good rain and moderate grazing pressure. Heavy grazing would destroy the freshly established perennial grass individuals.

2. **No change:** On DSP and RSP, a broad range of conditions exists both under moderate and heavy grazing pressure where the local population is kept in its previous condition. For locally extinct populations, no regeneration can be observed under average and below-average rainfall, because the primary productivity of annual grasses and forbs is too low to hide *Stipagrostis uniplumis* seedlings. On DSP, in years with good and average rain and moderate grazing (for heavy grazing, only in good rain years) there is enough annual and perennial biomass present to prevent the *Stipagrostis u.* individuals from pronounced damage.

3. **Pronounced damage:** A pronounced damage can be related to an unfavourable combination of rainfall and grazing pressure. Because DSP are used outside of the vegetation period, a pronounced damage is only observed in years with rains below average (including drought years). Additionally, under average rainfall a damage can occur if the biomass proportion of the perennial grasses is high (cover states 2 and 3) and grazing pressure is heavy. Here the readily available parts of the perennial tufts do not provide enough fodder for the whole year, and the cattle use lower, hard and rather unpalatable parts of the tufts, reducing the reserve biomass. On RSP, the grazing pressure all year through prevents the perennial grasses from a successful compensatory regrowth during the vegetation period. Here grazing will affect the ground cover and vitality of local population in all years except those with above-average rainfall. The only difference between moderate and heavy grazing is how severe the damage to the grass tufts is. Under heavy grazing, the local populations become extinct within only one year if rain is below average. Young or severely damaged populations are also destroyed in years with average rain.

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5 Synthesis

5.1 Pieces of a whole

This chapter aims to synthesise the findings of the study's three previous parts. Each part represents a theme and can be read as an autonomous unit. Together, they are important pieces of the study's broader approach that aims to fulfil the main objective: the identification of basic principles for sustainable grazing management in semi-arid regions.

The approach is characterised by the following features: Two case studies are taken as starting point, both representing existing, apparently successful, sophisticated grazing management systems. Using an ecological-economic model analysis, key factors for sustainable grazing management in these cases were determined. Due to large structural differences of the two land use systems, two simulation models, with different levels of detail, were constructed.

However, a clear focus is set on generating hypotheses with regard to the following question: Can the model results for sustainable grazing be generalised and do they hold for other grazing management systems in semi-arid regions as well? Such generalisation involves two steps: First, I tested whether these hypotheses hold in land use systems of similar structure as the one originally considered, but affected by global change (institutional change or climate change). In order to meet this goal, I used the corresponding model and carried out a parameter variation and a scenario analysis. In the second step, the test of the validity of the hypotheses was extended to land use systems that are structurally different, using the second simulation model.

Firstly, I want to highlight and discuss one particular factor identified as being important for sustainable grazing management: resting of parts of the pasture. Then, I want to point out a second central aspect of the study, this being the necessity of understanding the interplay between ecological and economic risk management strategies in achieving the main objective - the detection of basic principles for sustainable grazing management. Finally I discuss the performance and potential of my approach.

5.2 Crucial: Understanding the relevance and functioning of resting

A large number of studies, focussing on sustainable grazing strategies, place emphasis on stocking rate and hence on the intensity of grazing (e.g. Illius *et al.*, 1998; Weber *et al.*, 1998; Campbell *et al.*, 2000; Fynn & O'Connor, 2000). In contrast, the focus of this study is explicitly on pasture resting, stimulated by the investigation of two case studies where resting is a central part of the management system. The aim is to detect whether the inclusion of resting and the manner in which it is carried out is crucial for sustainable land use and whether the results can be generalised to other semi-arid rangelands.

The two case studies considered, the Gamis Farm and the land use system of the Ova-Himba, differ strongly with respect to their economic system. The Gamis Farm is a commercial Karakul sheep farm owned by a single farmer. The land use system of the Ova-Himba is a communally organised system managed by the cattle herders according to traditional rules, but recently affected by numerous changes. The farmer of the Gamis Farm applies a rotational grazing system and grants additional resting to a third of the pasture during the rainy season in years with sufficient rainfall. Ova-Himba herders ensured, with a strategy applied from 1960 to 1995, seasonal resting for parts of the pastures during the rainy season. Furthermore, grazing reserves were maintained for times of drought. Therefore, these pastures were effectively rested during years with sufficient rainfall.

In both model analyses I investigated whether and in which way resting is a crucial aspect of the grazing management system. The exploration reveals the following:

(1) The modelling analysis of the Ova-Himba (Chapter 4) indicates that granting of seasonal resting is highly important. The productivity of the traditional system with heterogeneous pasture use (high grazing pressure on rainy season pastures and resting in the rainy season of dry season pastures) sustains higher livestock numbers than would homogeneous but permanent use. This is despite the observation that heterogeneous use leads to higher degradation of rainy season pastures.

(2) The Gamis Farm case study reveals the importance of resting in wet years for an effective regeneration of the pasture (Chapter 2). Under certain ecological conditions, purely opportunistic strategies that closely adjust livestock number to the available forage without resting are not sufficient to ensure high livestock number. Resting is essential when the pasture has low regeneration potential. Additionally, the important role of unplanned rests for the pasture regeneration is revealed. These occur when livestock numbers are low due to a prolonged drought and therefore the entire pasture is not needed.

In conclusion, the investigation of the two case studies leads to an improved understanding about the functioning of pasture resting in general. Under certain ecological and climatic conditions, adapted resting regimes are crucial for an effective regeneration of the reserve biomass and to ensure high livestock numbers. In particular under low regeneration potential of the pasture, an adaptive management system, where livestock numbers are adapted to temporally and spatially heterogeneous biomass production in connection with resting, is appropriate. Specifically, resting of parts of the pasture during the rainy season, in particular in wet years, and thereby investing in reserve biomass, is essential under these conditions. It is important to note that the reserve biomass, representing the grazing and rain history, is the indicator for the ecological state of the pasture and acts as an ecological buffer of the system. In the short-term, abundant reserve biomass may smooth the fluctuations in green biomass coming from variability in rainfall. Over the long-term, the maintenance of reserve biomass is shown to be prerequisite to ensuring high green biomass production and hence high livestock production.

Furthermore, the limits for the relevance of resting can be detected: In contexts of high regeneration potential of the pasture (high regeneration rate of the biomass or high mean annual rainfall), resting periods are not needed for high livestock numbers to be maintained over the long-term. However, since semi-arid regions are characterized by low regeneration potential, I hypothesise a high value of resting (during the rainy season, and particularly in wet years) for sustainable use of semi-arid rangelands in general (see also Tainton & Danckwerts, 1999).

5.3 Indispensable: Understanding the interplay of ecological and economic risk management strategies

Grazing management in semi-arid regions is exposed to global change, in particular institutional change. Opportunities of economic risk management become available, provided by the government or the market. Considering that numerous governmental interventions aimed at reducing risks in the income of the farmers have failed, an understanding of the causes is crucial. A possible source of failure is inadequate consideration of feedback effects of economic measures on the ecological state of the pastures (Breman & De Wit, 1983; Milton *et al.*, 2003). I was, therefore, explicitly interested in the investigation of such feedback mechanisms. I explored the consequences of availability of economic risk management measures on the behaviour of the farmer. In particular, I studied whether a farmer, with access to economic risk management strategies, suspends ecological risk management strategies, such as resting in rainy years. (Chapter 3). This could negatively influence the long-term productivity of the pasture.

The study highlights that access to rain-index insurance as one example of economic risk management may influence the behaviour of the farmer and thus the long-term productivity of the pasture. A central result of this thesis demonstrates that the individual preferences of the farmer are decisive in determining whether he selects a different grazing strategy following access to insurance. In particular his time horizon is of importance: For long-term oriented farmers, grazing strategies with resting are optimal, regardless of whether there is access to rain-index insurance or not. For short-term oriented, risk-averse farmers, however, the availability of insurance leads to less resting (see also Wang & Hacker, 1997). This is a reflection of the fact that the short-term effect of resting - reducing the variability in the farmer's income - is compensated by the insurance, whereas its long-term effect - preserving the productivity of the pasture - is not necessary for a short-term thinker.

Feedback mechanisms were analysed for the case study of Ova-Himba in the same way (Chapter 4). The influence of the possibility of purchasing livestock on the ecological condition and on the livestock number over time was investigated. It emerged that, as long as the traditional strategy, i.e. including seasonal resting, is maintained, the possibility of purchasing leads to higher livestock number. When seasonal resting is not implemented, the negative impact on the ecological condition of the farm is so strong that much less livestock can be maintained in the long term.

My study confirms that an essential prerequisite for the implementation of new economic risk management measures is their ecological evaluation, including the explicit analysis of their feedback on the state of ecological pasture. The approach used in this study appears very promising and well-suited to fulfilling this requirement.

5.4 Promising: Potential of the approach presented

The study's approach, assessing existing, apparently successful management systems using ecological-economic modelling, is promising for detecting the key factors for sustainable grazing management within semi-arid systems. These systems are highly complex: While investigating ranges and limitations of the key factors identified, in particular with respect to global change, it was shown that the explicit consideration of the feedback mechanisms between ecological and economic factors is indispensable. In contrast to long established disciplines, Ecological Economics, dealing with these types of problems, is rather young and few standard methods for their resolution are available. Hence, using existing and apparently successful grazing strategies as a foundation is appropriate for a number of reasons. Firstly, the practicability of these strategies can be relied upon. Secondly, deeper exploration may stimulate new ideas and generate new hypotheses about basic principles for sustainable grazing management in general. As concluded, such a basic principle is resting in the rainy season, in particular in wet years. This study also supports the transfer of practised (indigenous) knowledge to scientific knowledge, as the investigation of existing and apparently successful grazing strategies can generate new scientific insights. Existing land use patterns and underlying rules are explored to understand the mechanisms behind, similarly to pattern oriented modelling, cf. Grimm *et al.* (1996, 2005).

Furthermore, for the two case studies considered, it is relatively simple to detect aspects of global change which may affect these land use systems in the near future. Ecological-economic modelling allows simple incorporation and investigation of potential changes in climatic and economic conditions: A systematic analysis using parameter variations, global sensitivity analysis and scenario analysis can be performed. Consequently the main objective, the development of hypotheses regarding key factors for sustainable grazing management, its ranges and limits, can be reached.

Additionally, the future potential of the approach can be seen. In connection with a scenario analysis, the two existing simulation models can be used to tackle newly arising questions. To point out just one such question: it is of major interest to detect which socio-economic conditions (internal and external) are a prerequisite for sustainable land use. In the Ova-Himba case study, an increasing population generates a current problem for sustainability. The same resources support a growing number of people. Connected with this issue is the general problem of the minimal size of a farm or available pasture to allow a sustainable grazing management. For instance resting a third of the pasture and thus investing in the future yields is barely possible for subsistence farmers with low income who struggle to ensure their livelihood on a day to day basis. This issue is of major concern for policy makers, involved in land reform processes in semi-arid regions.

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Deutsche Zusammenfassung

Aride oder semi-aride Gebiete bedecken ein Drittel der Erdoberfläche. Sie sind gekennzeichnet durch geringe mittlere, aber stark schwankende Niederschläge. Die Lebensgrundlage von mindestens einer Milliarde Menschen hängt von der Nutzung dieses Landes ab, auf dem vorrangig Weidewirtschaft betrieben wird. 85% des bewirtschafteten Landes in Afrika wird beispielsweise für Viehzucht genutzt.

Desertifikation (oder auch Degradation genannt) - der Verlust von nutzbarem Weideland - ist ein hochaktuelles, globales Problem und verursacht enorme ökonomische und soziale Kosten. Weltweit werden die jährlichen Einkommensverluste durch Degradation von landwirtschaftlich genutztem Land in semi-ariden Gebieten auf 42 Milliarden US-Dollar geschätzt. Die Ursachen werden in klimatischer Variabilität und unangepassten Nutzungsstrategien gesehen. Sie sind aber bis heute von der Wissenschaft nicht vollständig verstanden.

Beweidung in ariden Gebieten ist gekennzeichnet durch starke Rückkopplungen zwischen den ökologischen und ökonomischen Faktoren. Auf der einen Seite ist der ökonomische Ertrag direkt abhängig vom ökologischen Zustand des Weidelandes und aufgrund des stark schwankenden Niederschlages äußerst risikobehaftet. Auf der anderen Seite können die ökologischen Ressourcen durch unangepasste Nutzung degradieren.

Angepasste Beweidungsstrategien sind notwendig, um auf den unvorhersehbaren und schwankenden Regen reagieren zu können. Globaler Wandel, wie beispielsweise Zugang zu neuen Maßnahmen des Risikomanagements, verbesserte Infrastruktur und Bevölkerungswachstum, beeinflusst in starkem Maße die Nutzungssysteme. In diesem Zusammenhang ist es von großer Bedeutung, ökonomische Risikomanagementmaßnahmen zu entwickeln, die Schwankungen im Einkommen verringern, sich aber nicht nachteilig auf den ökologischen Zustand des Weidelandes auswirken.

Diese Arbeit hat zum Ziel, zur Identifikation von Grundprinzipien nachhaltiger Beweidung beizutragen. Als Ausgangspunkt für anschließend umfassendere Untersuchungen wurden zwei Landnutzungssysteme gewählt, die sich in der Praxis bewährt haben. Es wurde die Methode der ökologisch-ökonomischen Modellierung verwendet, um Hypothesen über Grundprinzipien nachhaltiger Beweidung zu generieren und ihre Übertragbarkeit auf andere ökologische bzw. sozio-ökonomische Rahmenbedingungen zu testen. Modellierung ist besonders geeignet, um Wirkungszusammenhänge in semi-ariden Gebieten zu verstehen, da Auswirkungen von deren Nutzung oft erst nach langen Zeitspannen sichtbar werden.

Unter nachhaltiger Nutzung wird in dieser Arbeit der langfristige Erhalt der Produktivität des Weidelandes verstanden, unter Berücksichtigung, dass gleichzeitig ausreichendes Einkommen für die Landnutzer erzielt wird.

Die zwei untersuchten Fallbeispiele, beide aus Namibia, unterscheiden sich stark hinsichtlich des Wirtschaftssystems. Das erste Fallbeispiel ist die kommerzielle Karakulschaf-Farm Gamis. Der Farmer wendet eine flexible Strategie an, die zum einen die Besatzdichte des Viehs kurzzeitig an die verfügbare Futtermenge anpasst und zum anderen die Vegetation durch Ruhepausen für ein Drittel des Weidelandes in Jahren mit ausreichendem Niederschlag langfristig schont.

Beim zweiten Fallbeispiel handelt es sich um das Nutzungssystem der halbnomadisch lebenden Ova-Himba im Norden des Landes. Bis vor kurzem wendeten sie für das Halten von Rindern und Kleinvieh ein komplexes Managementsystem an. Dazu gehörte eine regenzeit-abhängige Nutzung, bzw. Schonung von Weiden und das Reservieren von Weiden für Notzeiten, sowie das Erlassen von Sanktionen bei Regelbrüchen. Die Weiden in unmittelbarer Umgebung der Siedlungen wurden das ganze Jahr (mehr oder weniger intensiv) genutzt. Aufgrund der politischen Umstände waren sie in den vergangenen Jahrzehnten zu reiner Subsistenzwirtschaft gezwungen. Seit wenigen Jahren hat sich das Managementsystem aufgrund veränderter sozio-ökonomischer Rahmenbedingungen teilweise gewandelt.

Obwohl beide Managementsysteme das Weideland zeitlich und räumlich in unterschiedlicher Art und Weise nutzen, weisen sie entscheidende Gemeinsamkeiten auf: die Bedeutung von Ruhepausen für das Weideland und die flexible Anpassung der Viehzahlen an die vorhandene Futtermenge.

Die Dissertation gliedert sich in drei Teile, die unabhängig voneinander lesbar sind. Nach einer allgemeinen Einführung in diese Arbeit (Kapitel 1), untersucht der erste Teil die Funktionsweise der Schonung von Flächen und deren Bedeutung für die Produktivität semi-ariden Weidelandes (Kapitel 2). Ausgehend von der Beweidungsstrategie auf der Gamis-Farm wurde analysiert, unter welchen klimatischen und ökologischen Bedingungen Schonung im Allgemeinen, und in regenreichen Jahren im Speziellen, für die Regeneration der Weiden von Bedeutung ist. Deswegen wurde diese Strategie mit Beweidungsstrategien verglichen, die die Viehzahlen ebenso an die vorhandene Futtermenge anpassen, aber im Gegensatz zur Gamis-Strategie entweder gar nicht oder in trockenen Jahren schonen. Dazu wurde ein abstraktes, konzeptionelles ökologisches Simulationsmodell konstruiert.

Bei dieser Analyse zeigte es sich, dass das Gewähren von Ruhepausen in regenreichen Jahren für den Erhalt der langfristigen Produktivität des Weidelandes bei geringem Regenerationspotential der Vegetation essentiell ist. Denn diese Strategie führt zu einem effektiven Aufbau und einer effektiven Nutzung eines wichtigen ökologischen Puffers im System, der Reserve-Biomasse. Darunter werden die unter- und oberirdischen Reserve-Organe der Pflanze verstanden, die nicht der Photosynthese dienen und in denen somit die Regen- und Beweidungsgeschichte gespeichert ist. Für den Aufbau der Reserve-Biomasse wird außerdem die Bedeutung von so genannten ungeplanten Ruhepausen nach lang anhaltenden Dürren herausgestellt. Sie treten auf, falls die Viehzahlen durch die Dürre stark zurückgegangen sind, kein Vieh zugekauft wird und somit nicht das gesamte Weideland genutzt wird.

In Teil 2 (Kapitel 3) wird das für die Beantwortung von ökologisch-ökonomischen Fragestellungen erweiterte Simulationsmodell vorgestellt. Mit seiner Hilfe wurden die Wechselwirkungen zwischen ökologischen und ökonomischen Risikomanagementstrategien explizit untersucht. Es zeigt sich, dass das Schonen der Weiden in regenreichen Jahren als risiko-reduzierende Strategie wirkt. Diese Strategie vermag die kurzzeitigen Schwankungen in den Erträgen des Farmers zu verringern und dient gleichzeitig als Investition in die Produktivität des Weidesystems auf lange Sicht.

Es wurde der Frage nachgegangen, welchen Einfluss ökonomische Risikomanagementmaßnahmen auf die Wahl der Beweidungsstrategie des Farmers und damit auf den Zustand des Ökosystems haben. Als Beispiel werden Regen-Index-Versicherungen betrachtet. Bei Abschluss einer solchen Versicherung erhält der Farmer eine Auszahlung, sobald der Niederschlag unter einen vorher festgelegten Grenzwert fällt. Als Entscheidungskriterium des Farmers wird ein Safety-First Kriterium zugrunde gelegt. Dieses besagt, dass der Farmer jährlich erst einen festgelegten Einkommensschwellenwert (beispielsweise ein Existenzminimum) mit einer gewissen Wahrscheinlichkeit erreichen möchte, bevor er darauf abzielt, sein erwartetes Einkommen zu maximieren.

Die Untersuchung zeigt, dass es stark von den Präferenzen des Entscheidungsträgers abhängt, ob eine andere Beweidungsstrategie bei Zugang zu Versicherungen gewählt wird. Die Analysen belegen, dass bei bestimmten Präferenzen des Farmers (relativ kurzer Zeithorizont und gleichzeitig hohe Risikoaversion) der Zugang zu Versicherungen dazu führt, dass die ökologische Managementstrategie - Schonen des Weidelandes in regenreichen Jahren - nicht mehr durchgeführt wird. Damit kann es auf lange Sicht zu einer Verschlechterung des ökologischen Zustandes der Farm kommen.

Der dritte Teil (Kapitel 4) analysiert das Weidemanagementsystem der Ova-Himba. Ein eigenes ökologisches Modell wurde konstruiert, welches die wichtigsten Aspekte der Weideregeln der Ova-Himba einbezieht und deren Wirkungen auf den verschiedenen Weideflächen, hinsichtlich Produktivität und Artenzusammensetzung der Vegetation, sowie die Rinderpopulation abbildet. Die bis vor kurzem angewendete Strategie der Ova-Himba wurde verglichen mit hypothetischen Weidestrategien, bei denen jeweils bestimmte Aspekte dieser so genannten traditionellen Strategie abgeändert wurden. Damit wurde der Frage nachgegangen, welche Aspekte der traditionellen Strategie für eine nachhaltige Nutzung essentiell sind. Dies ist momentan äußerst relevant, da, wie bereits erwähnt, die internen und externen sozio-ökonomischen Rahmenbedingungen für die Ova-Himba stark von Veränderungen betroffen sind.

Die Ergebnisse zeigen, dass zwei Aspekte für eine nachhaltige Nutzung von großer Bedeutung sind. Zum einen ist dies die intra-annuelle heterogene Beweidung aufgrund des Schonens von Teilen der Weide in der Regenzeit. Zum anderen gehört dazu die inter-annuelle heterogene Beweidung infolge des Reservierens von Weiden für Zeiten lang anhaltender Dürre. Dies führt analog dem Fallbeispiel Gamis-Farm zu einem effektiven Aufbau der Reserve-Biomasse. Diese ist in diesem Fall repräsentiert durch den Grad der Bodenbedeckung durch mehrjährige Gräser und durch den Zustand der Samenbanken der einjährigen bzw. mehrjährigen Gräser. Es lässt sich feststellen, dass das von den Ova-Himba angewendete heterogene Nutzungssystem zwar auf der einen Seite lokal zu einer Degradation der stark ganzjährig genutzten, unmittelbar um die Siedlungen gelegenen Weiden führen kann, insgesamt betrachtet, aber zum Erhalt der Produktivität des Gesamtsystems beiträgt.

Die Dissertation schließt mit einem Kapitel (Kapitel 5), dessen Aufgabe es ist, die zentralen Ergebnisse der drei Teile in den umfassenderen, zugrunde liegenden Forschungsansatz einzuordnen. Wie bereits ausgeführt, geht dieser Forschungsansatz von existierenden, erfolgreichen Beweidungsstrategien aus, um Hypothesen über Grundprinzipien nachhaltigen Beweidungsmanagements in semi-ariden Gebieten mit Hilfe der ökologischen-ökonomischen Modellierung zu generieren. Es zeigte sich, dass mit dieser Methode Rückkopplungsmechanismen zwischen den ökologischen und ökonomischen Faktoren explizit analysiert werden können. Deswegen hat sie sich als sehr geeignet erwiesen, die Übertragbarkeit der für die beiden Fallbeispiele identifizierten Grundprinzipien auf andere klimatische, ökologische und ökonomische Rahmenbedingungen zu untersuchen. Aus diesem Grund konnten wichtige Beiträge für ein tieferes Verständnis des Gültigkeitsbereichs und der Grenzen einer Generalisierung der Ergebnisse geleistet werden.

Dieser Ansatz erweist sich zudem als viel versprechend, um zukünftig weitere in diesem Kontext relevante Forschungsfragen anzugehen. Beispielhaft sei hier eine erwähnt: In Zeiten des überall auftretenden globalen Wandels ist es von großem Interesse herauszufinden, welche sozio-ökonomischen Rahmenbedingungen überhaupt ein nachhaltiges Wirtschaften ermöglichen. So ist das Gewähren von Ruhepausen für Teile des Weidelandes nur möglich, wenn die Farm bzw. das zur Verfügung stehende Weideland eine gewisse Mindestgröße haben. Diese Erkenntnisse könnten von großer Relevanz für Entscheidungsträger sein, die in Landreformprozesse in semi-ariden Gebieten involviert sind.

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